Recent results from Coulomb Dissociation (CD) experiments

Tohru Motobayashi
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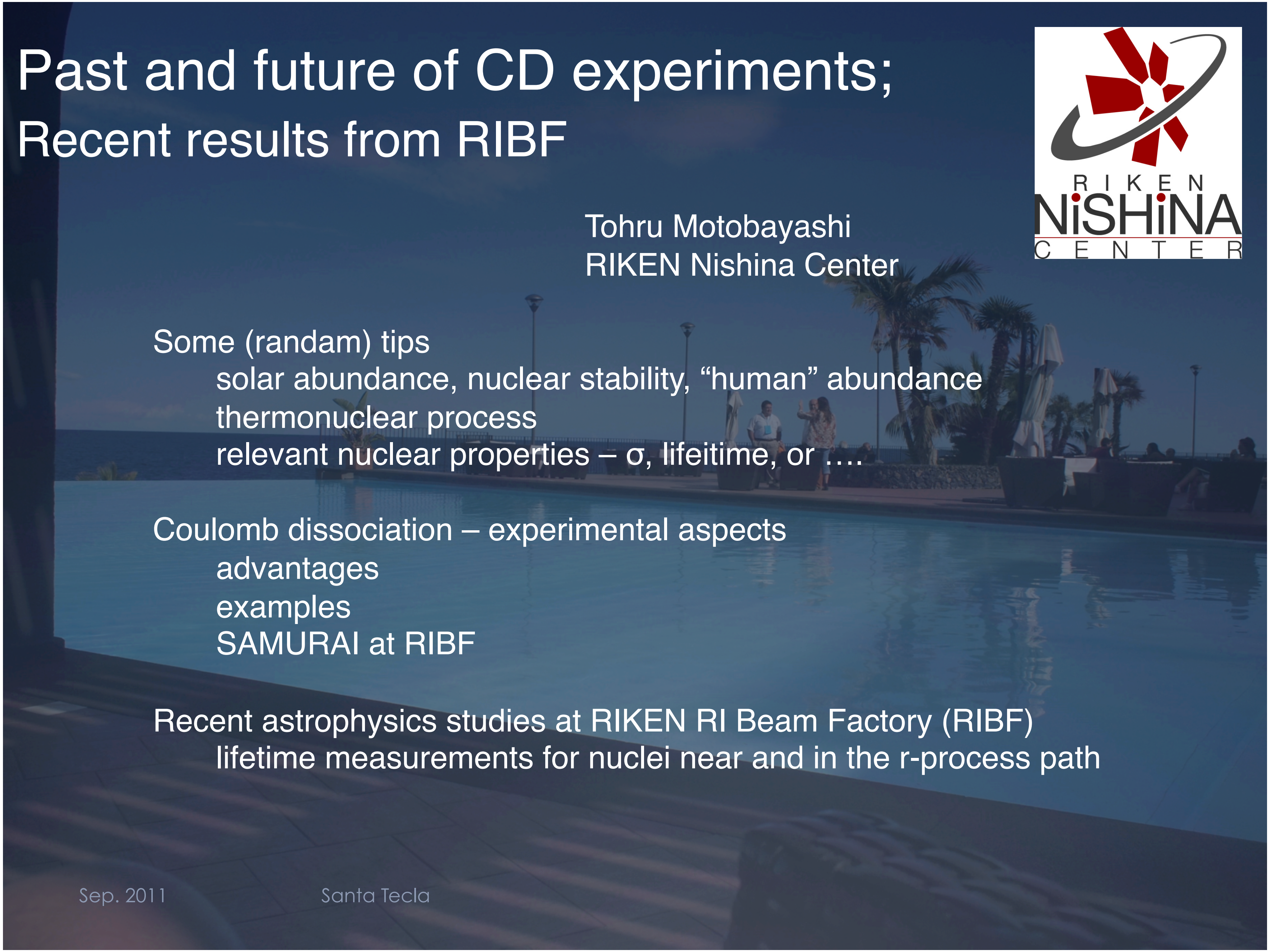
Sep. 2011

Santa Tecla



Past and future of CD experiments;
Recent results from RIBF

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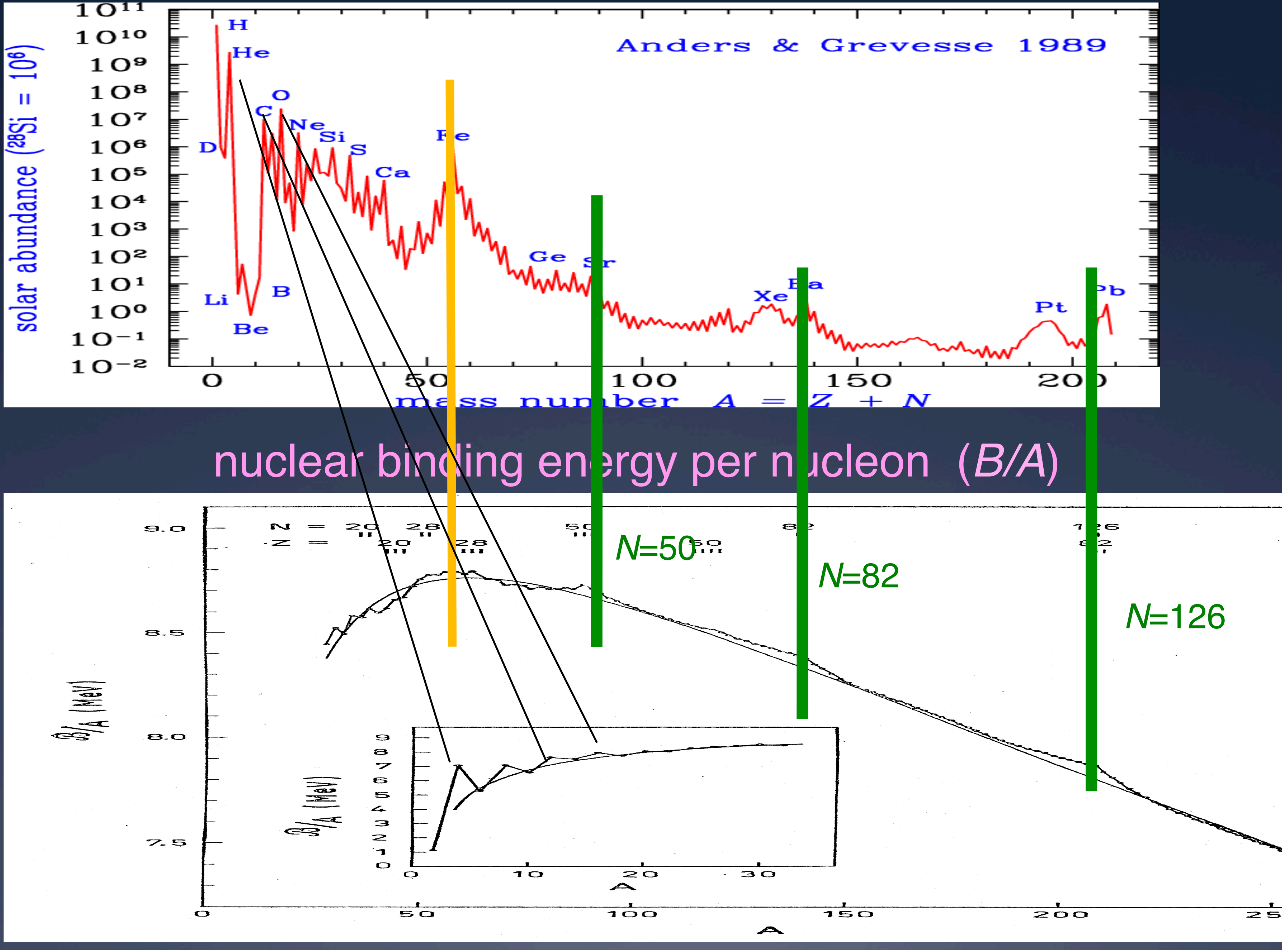
Some (randam) tips
- solar abundance, nuclear stability, “human” abundance
- thermonuclear process
- relevant nuclear properties – σ, lifeitime, or ….

Coulomb dissociation – experimental aspects
- advantages
- examples
- SAMURAI at RIBF

Recent astrophysics studies at RIKEN RI Beam Factory (RIBF)
- lifetime measurements for nuclei near and in the r-process path

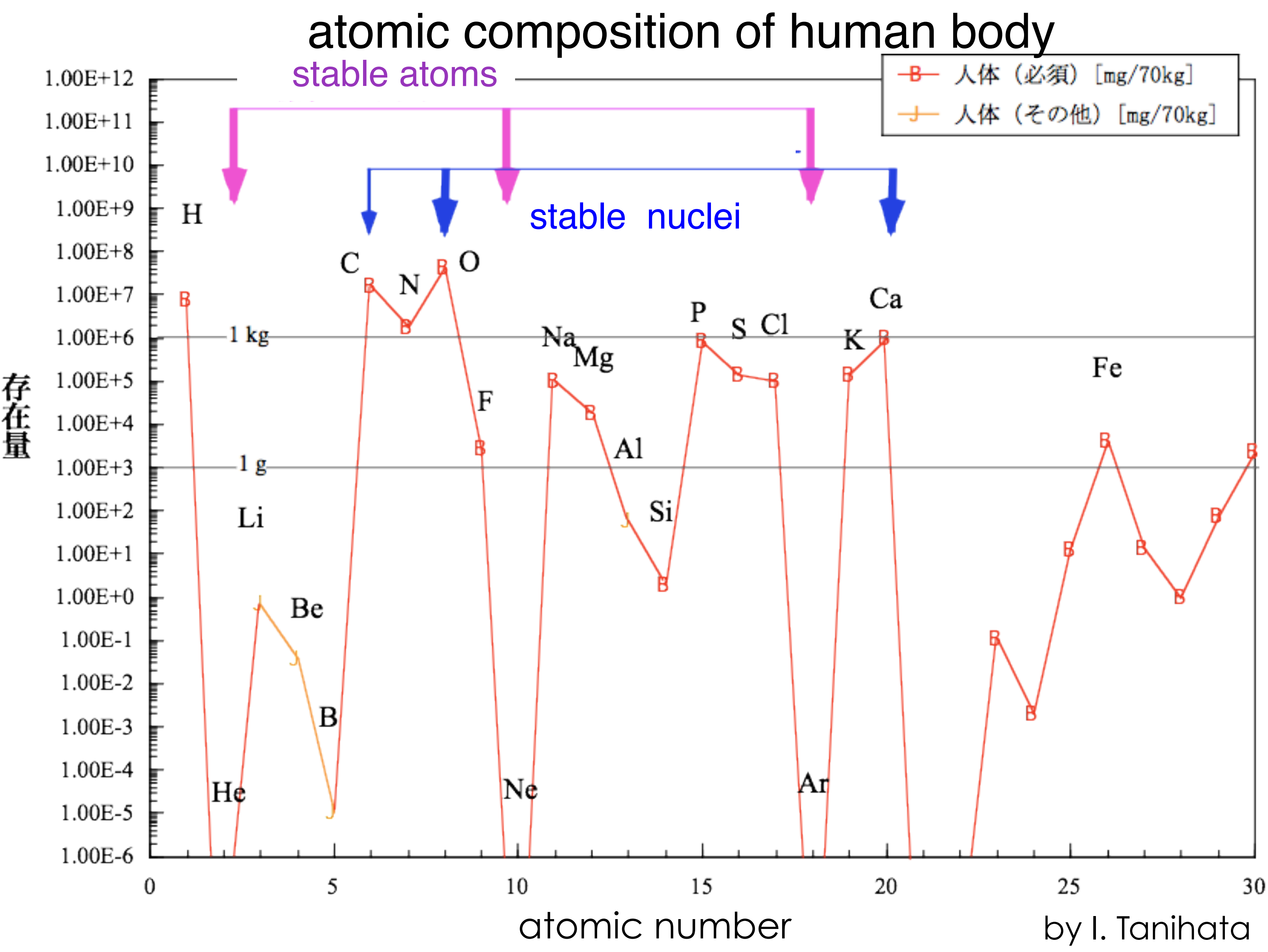
Abundance and nuclear stability are correlated.



nuclear binding energy per nucleon (*B/A*)

By the way… Atomic and nuclear stabilities are different. (lucky)

If the magic numbers are common to atom and nucleus, ……



atomic composition of human body

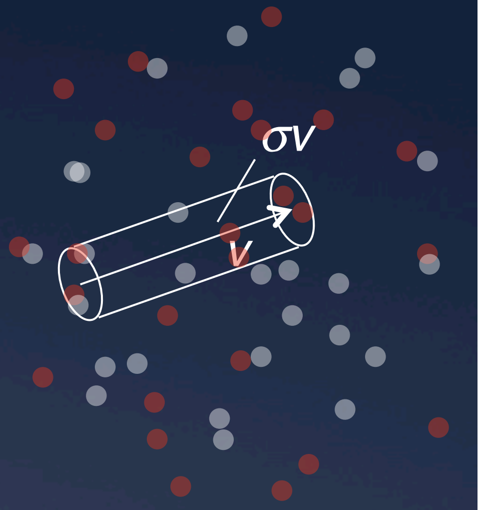
by I. Tanihata

Reaction rate is obtained by the Maxwellian average of σ.

Number of reaction per unit time and unit volume

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu_{12} (kT)^3} \right)^{1/2} \int dE \sigma(E) E \exp\left[-\frac{E}{kT} \right]$$



Hot and dense gas

For charged particles: σ ← Coulomb penetration (tunnel effect)

e.g.
$T = 1.5 \times 10^7$ K (sun) → kT = 1.3 keV (E_G = 20 keV)
much lower than the Coulomb barrier

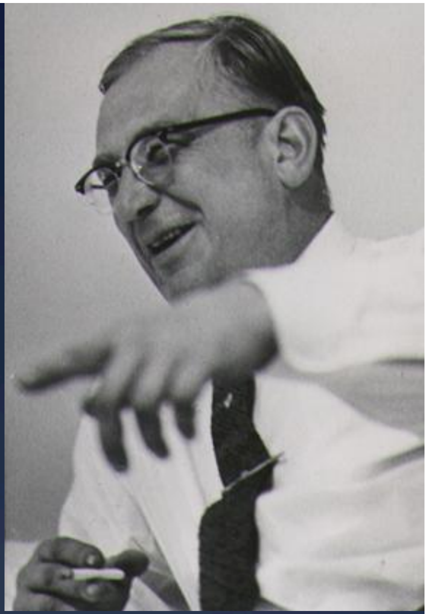
astrophysical *S*-factor ~ constant *v.s. E*

$$S = \sigma E \exp[2\pi\eta]$$

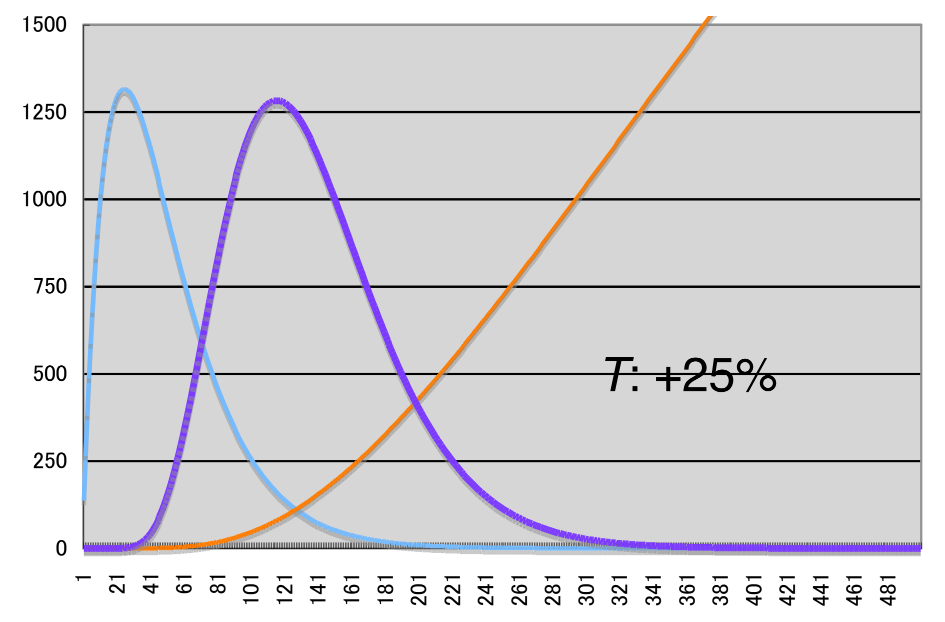
$$\eta = e^2 Z_1 Z_2 / \hbar v$$

The most probable energy is higher than *kT*.

"Gamow peak"



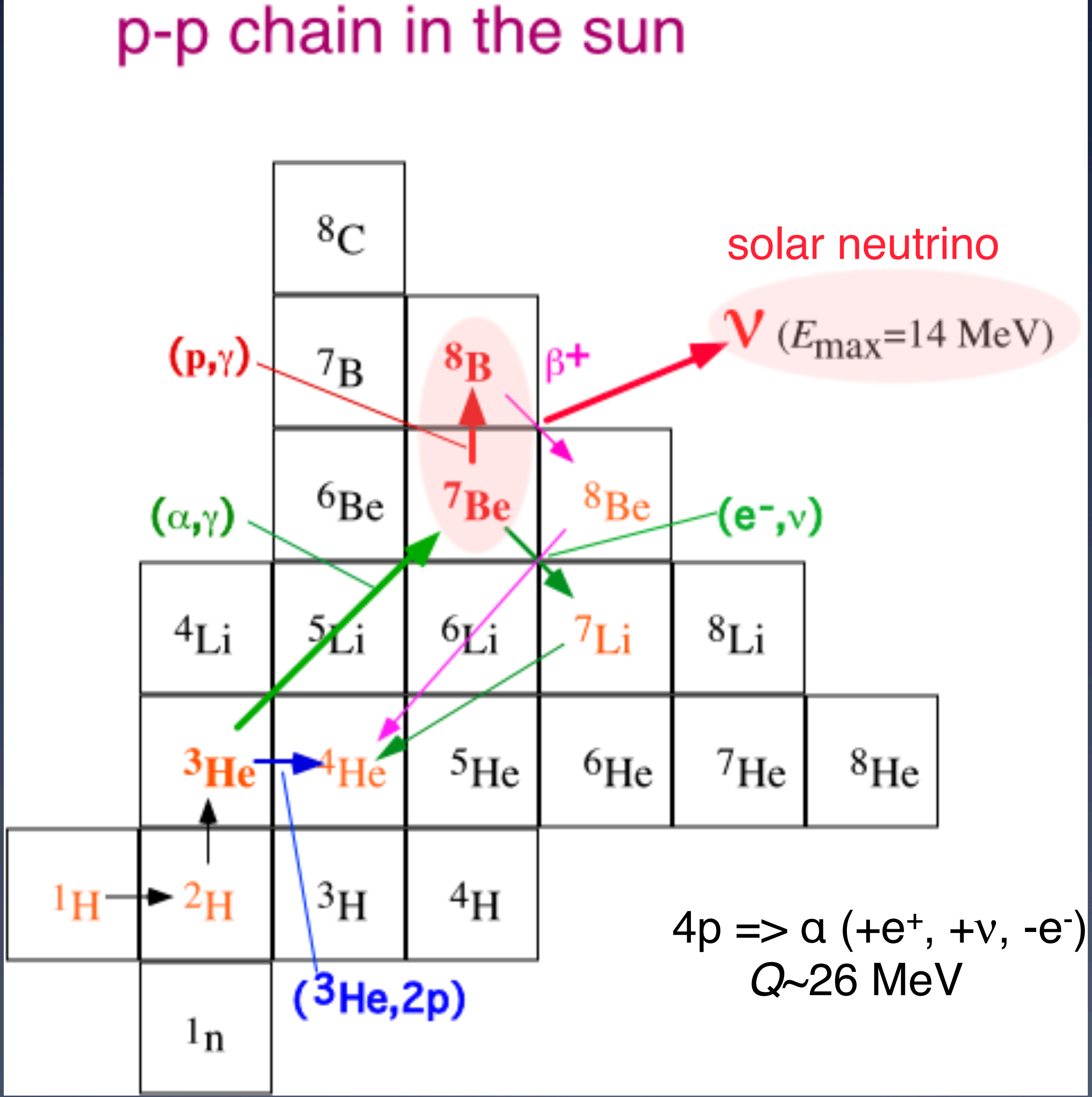
Reaction rate <σv> depends strongly on *T*.



$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu_{12} (kT)^3} \right)^{1/2} \int dE\, \sigma(E) E \exp\left[-\frac{E}{kT} \right]$$

assuming constant *S*

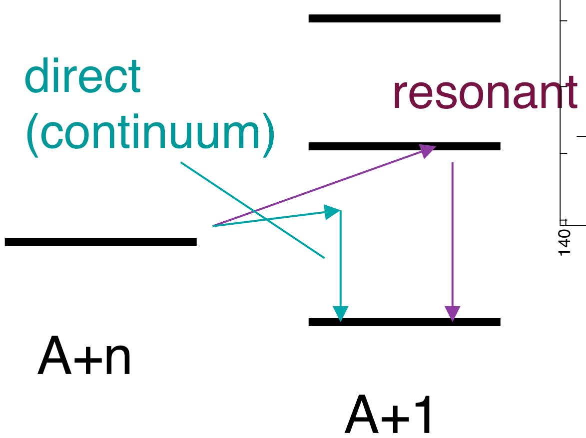
Competition between reaction (p-capture) and β⁺ decay ➔ measurements of σ / lifetime

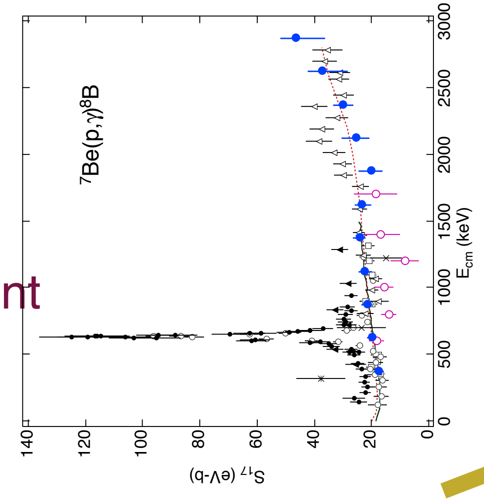


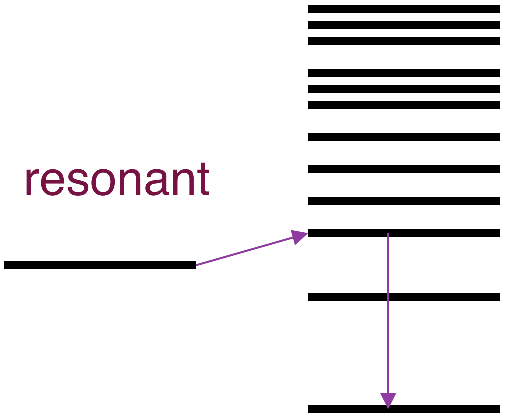
4p => α (+e⁺, +ν, -e⁻)
Q~26 MeV

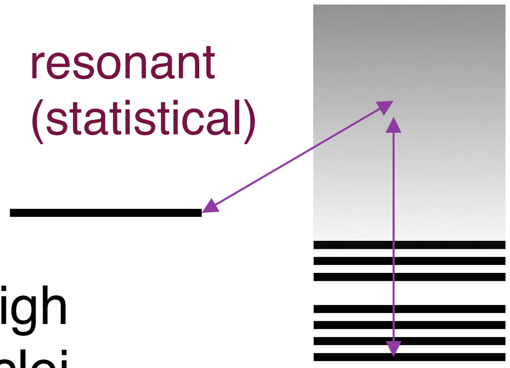
Situation depends much on the region in the nuclear chart.

(n,γ) (or (p,γ)) – radiative capture









level density: low

light nuclei

closed shell

near the drip line

Cross section (σ), lifitime

Direct measurement

Indirect methods

Coulomb dissociation, ANC,….

mass (Q), lifetime

level density ..

level density: high

heavier nuclei

Process can be (mostly) controlled by the reaction *Q*-values (not by σ). *e.g.* r-process

equilibrium in explosive conditions: between the inverse processes
e.g. radiative capture ←→ photo-disintegration

Saha equation for A+n ←→ (A+1)+γ

$$\frac{N(Z,A+1)}{N(Z,A)} = N_n \left(\frac{h^2}{2\pi m_{An} kT}\right)^{3/2} \frac{2j_{Z,A+1}+1}{(2j_{Z,A}+1)(2j_n+1)} \frac{G^{norm}_{Z,A+1}}{G^{norm}_{Z,A}} e^{Q_{n\gamma}/kT}$$

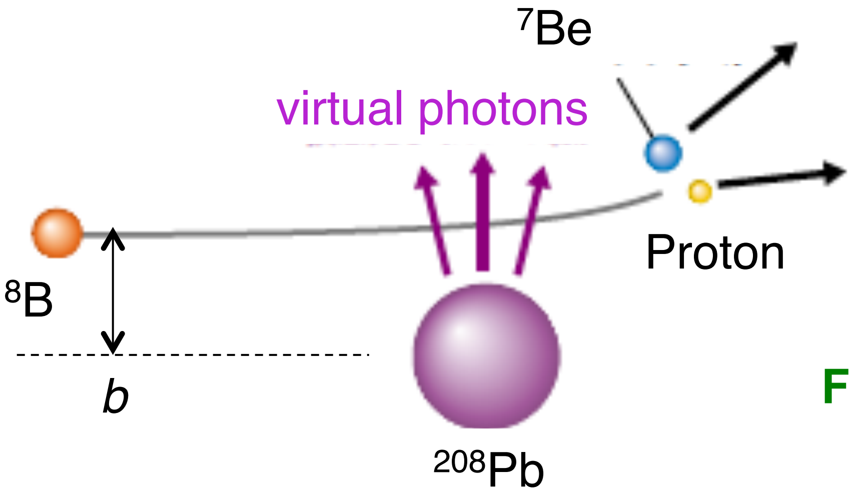
level (density)
temperature

nuclear mass

$Q_{ng} = m(A)c^2 + m(n)\, c^2 - m(A+1)\, c^2$

Coulomb dissociation   an indirect method for σ measurements
= photodisintegration by virtual photon

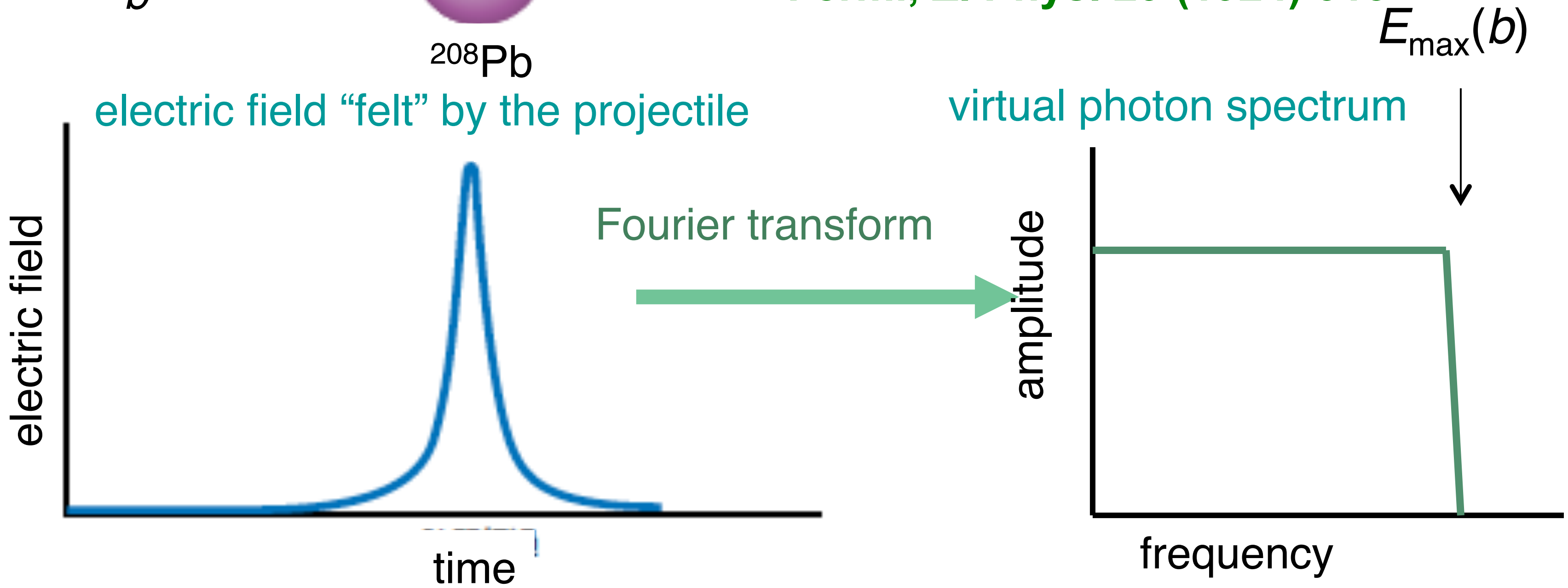
(γ Trojan Horse)



E_{in} ↗ : E_{max} ↗

b ↗ : E_{max} ↘

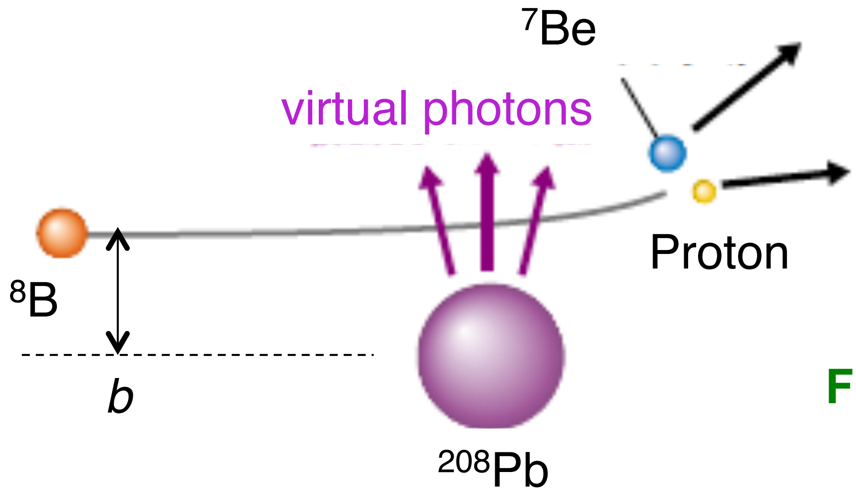
Fermi, Z. Phys. 29 (1924) 315



frequency
~ photon energy
($E=h\nu$)

Coulomb dissociation   an indirect method for σ measurements
= photodisintegration by virtual photon

(γ Trojan Horse)



E_{in} ↗ : E_{max} ↗

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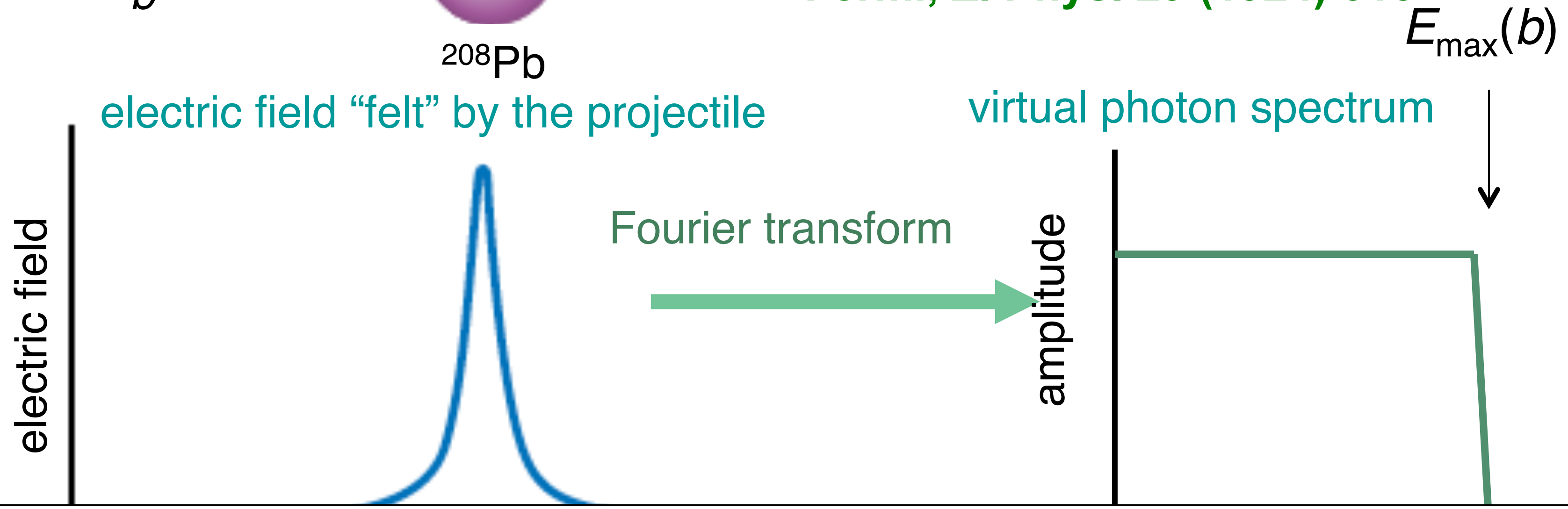


electric field “felt” by the projectile

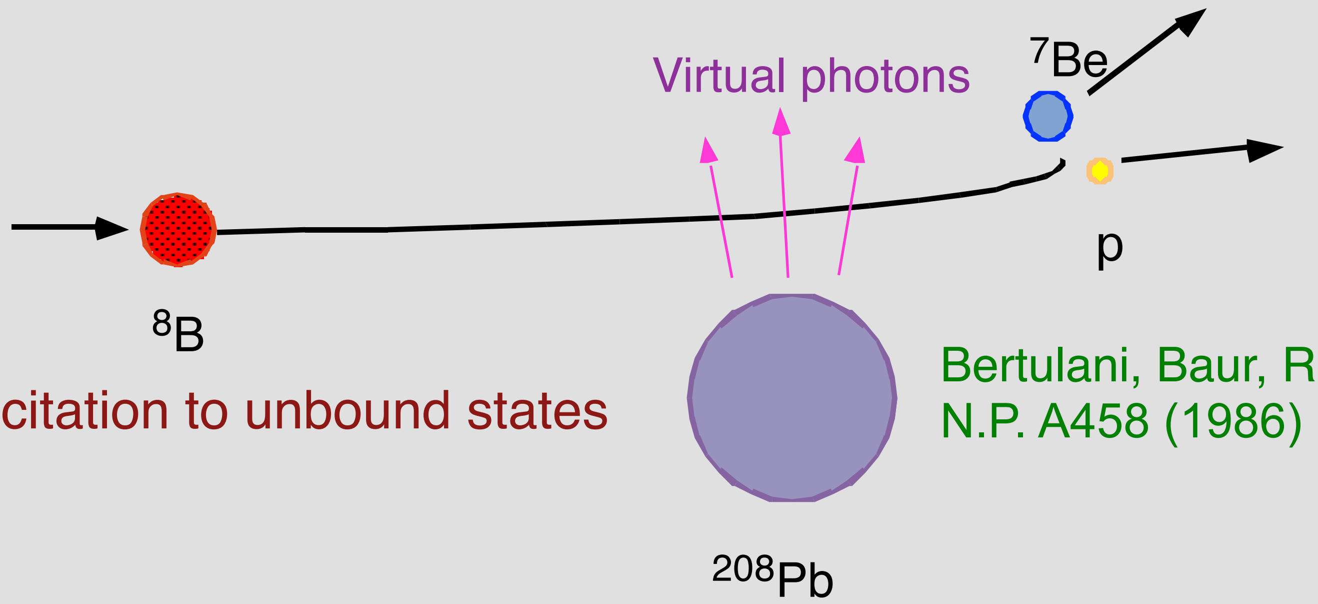
virtual photon spectrum

“Fast beam” can cover the energy range of nuclear excitation.

~ photon energy

($E=h\nu$)

Coulomb dissociation successfully applied to astrophysical capture reactions



= Coulomb excitation to unbound states

Bertulani, Baur, Rebel
N.P. A458 (1986) 188

^{8}B+^{208}Pb -> ^{7}Be+p+^{208}Pb (C.D.)

↓ virtual photon theory or DWBA

^{8}B(γ,p)^{7}Be (abs.)

↓ detailed balance

^{7}Be(p,γ)^{8}B (capt.)

large σ, thick target (intermediate energy)

experiments with weak RI beams

Coulomb dissociation efficient tool ← σ enhancement and experimental advantages

detailed balance

$$\sigma_{(\gamma,\mathrm{p})} = \frac{(2j_7+1)(2j_1+1)}{2(2j_8+1)} \boxed{\frac{k_{17}^2}{k_\gamma^2}} \sigma_{(\mathrm{p},\gamma)}$$

100 ~ 1000

virtual photon number (intermediate energy)

$$\left(\frac{d\sigma}{dE_\gamma}\right)_{\mathrm{C.D.}} = \frac{\boxed{n}}{E_\gamma}\sigma_{(\gamma,\mathrm{p})}$$

100 ~ 1000

thick target

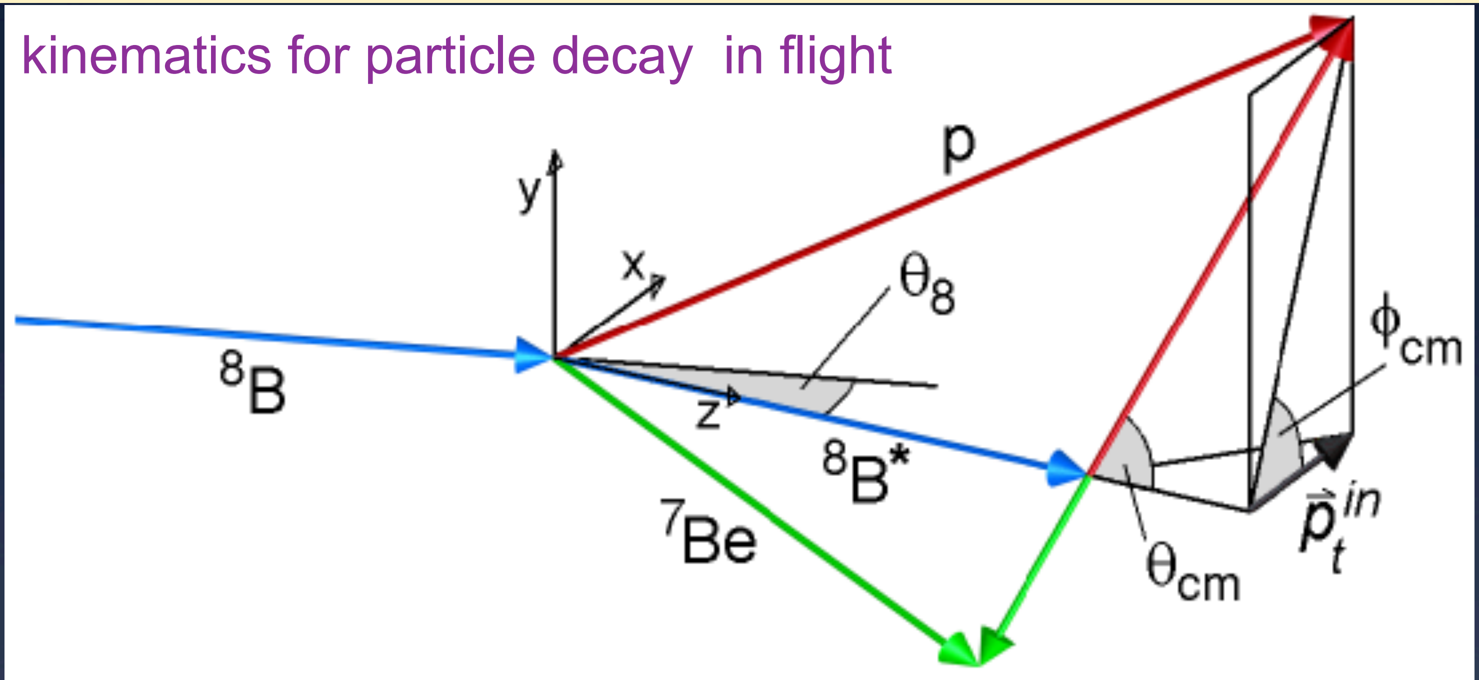
charged particle detection

but

Indirect --- nucl. force / higher order / E2 / relativistic effects…

← reaction theory

Invariant mass (relative energy) measurement



ΔE_{rel} : Independent of ΔE_{in}

good for experiments with poor-quality RI beams

$$\Delta E_{\mathrm{rel}} \approx 2\sqrt{\frac{A_1 A_2}{A_1 + A_2}}\sqrt{T_0 E_{\mathrm{rel}}}\,\Delta\chi$$

$$\Delta\chi = \Delta\theta,\ \Delta v / v$$

p+X, T_0=100 *A*MeV, E_{rel}=1 MeV,

Δq=0.5 deg. Δv=1%

↓

ΔE_{rel}=200 keV

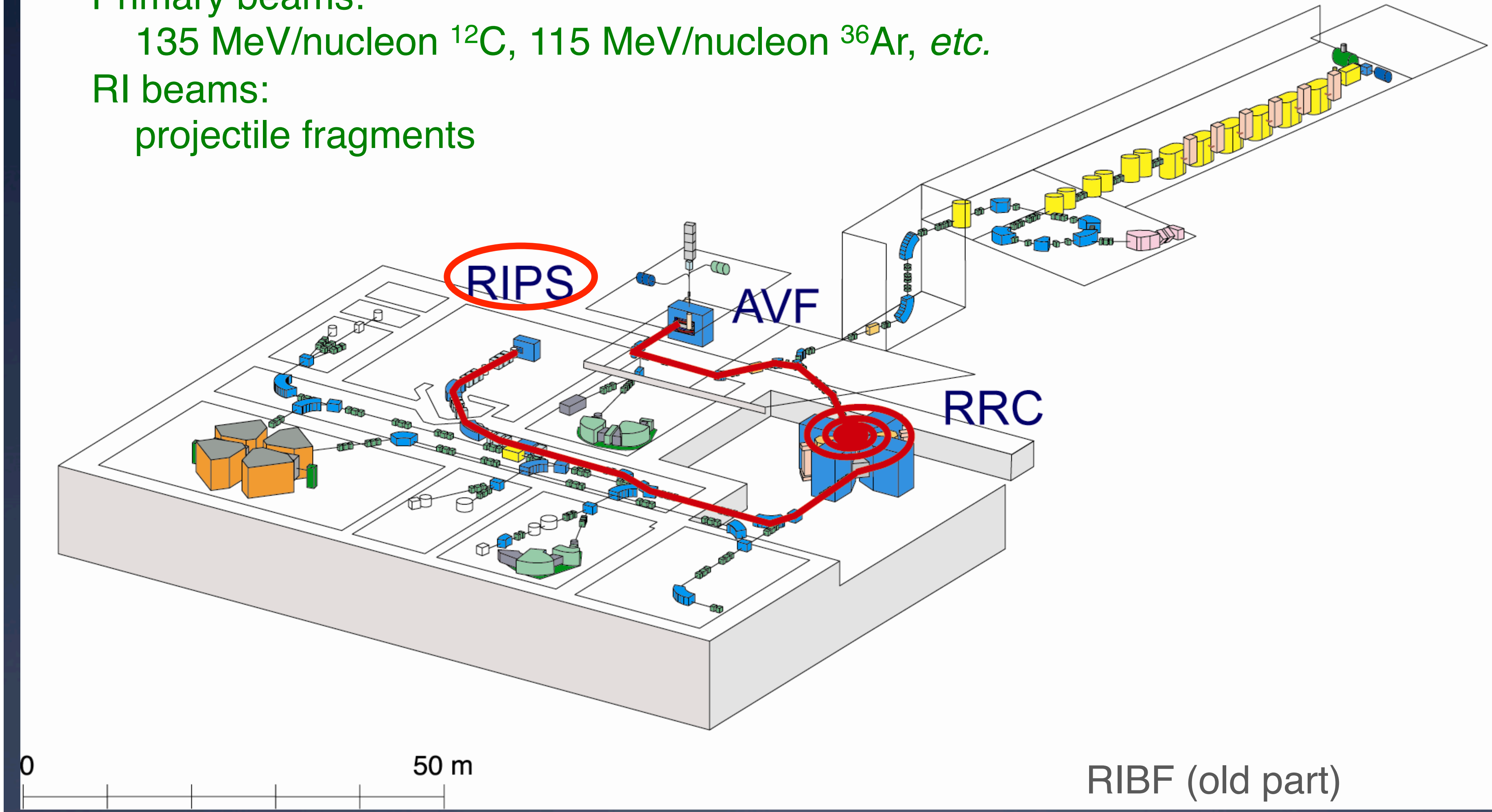
Experiments at RIPS, RIKEN RIBF

Primary beams:

135 MeV/nucleon ^{12}C, 115 MeV/nucleon ^{36}Ar, *etc.*

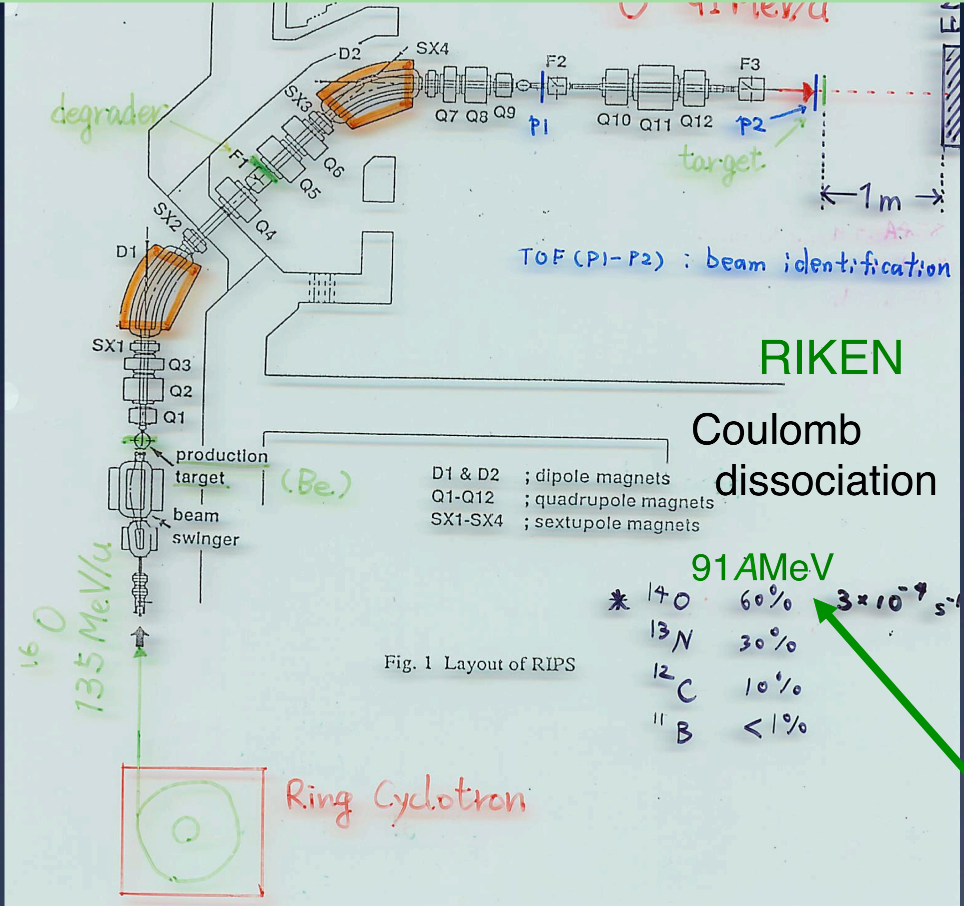
RI beams:

projectile fragments



RIBF (old part)

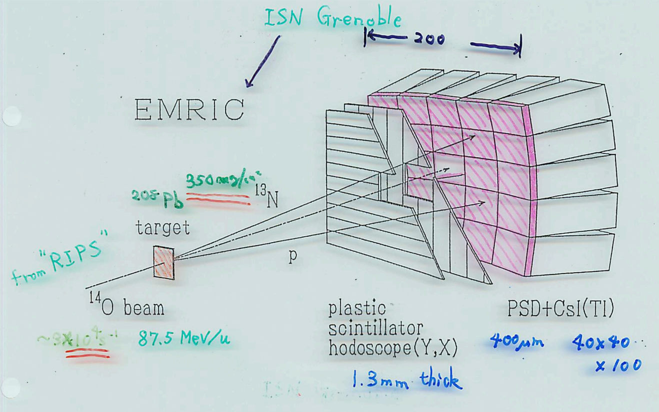
Experiments at RIKEN (CD) and Louvain la Neuve (direct) on $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$

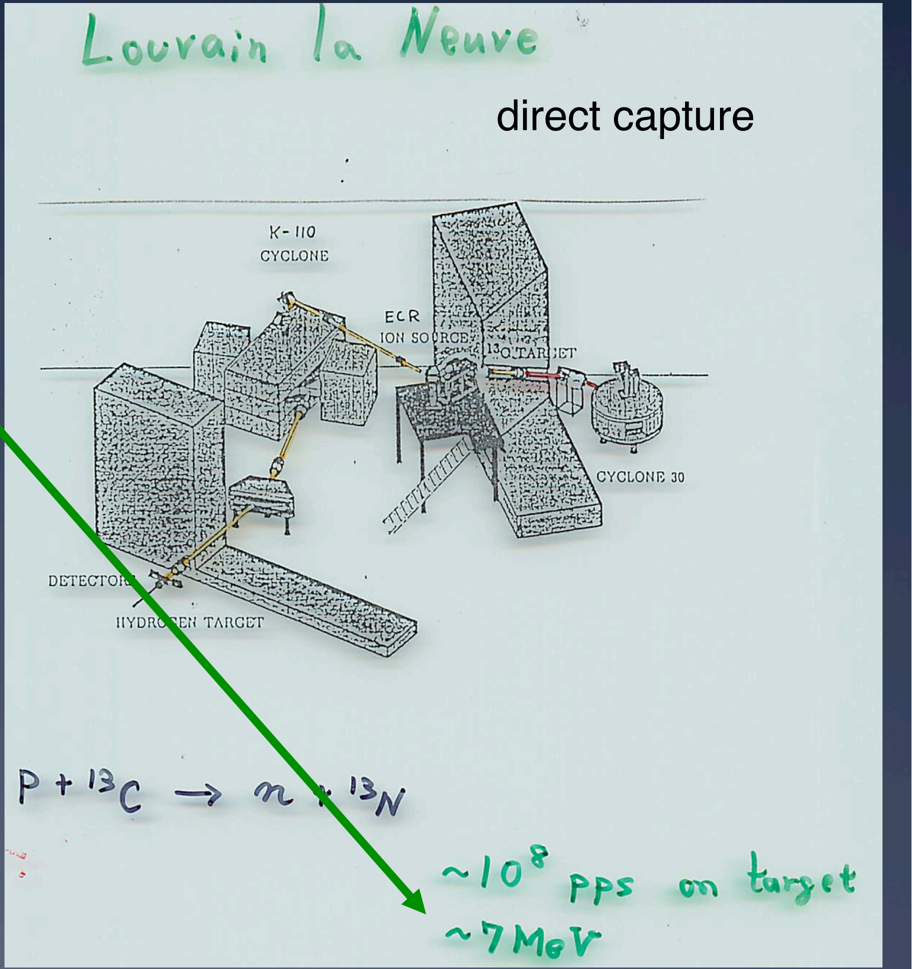


RIKEN

Coulomb dissociation

91*A*MeV





direct capture

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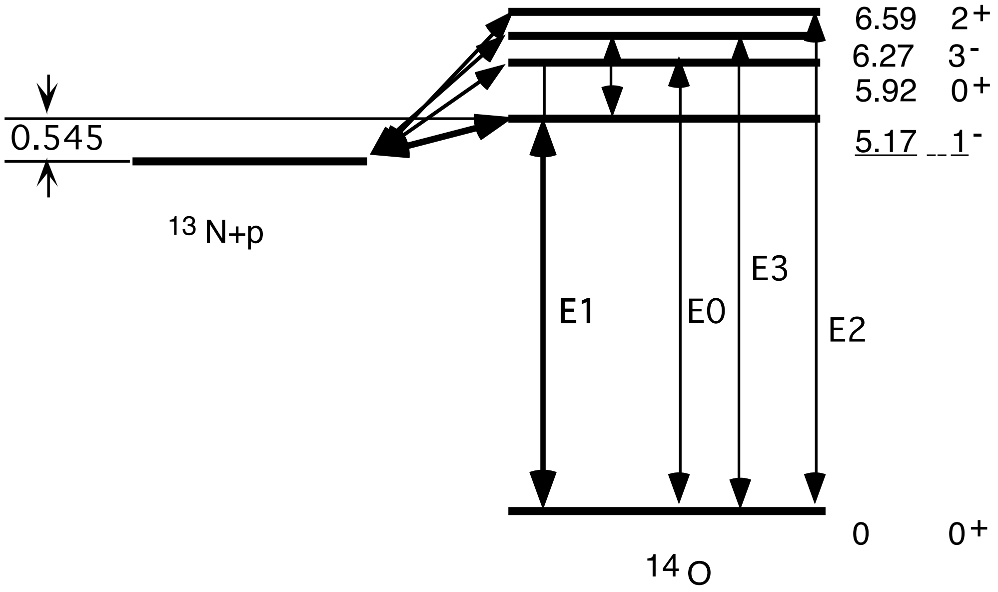
$^{13}N(p,\gamma)^{14}O$ – CNO *v.s.* hot CNO

In hot CNO cycle,
^{13}C is bypassed.
faster cycle.

^{14}O: $t_{1/2}$ = 1min.

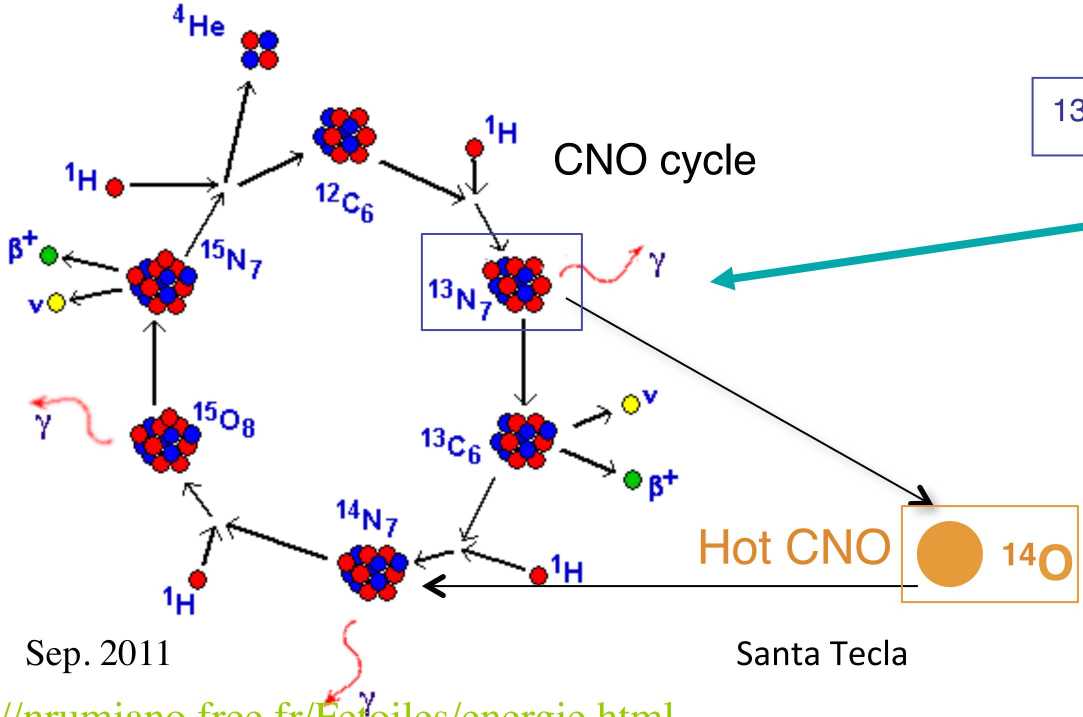


^{13}N: $t_{1/2}$ = 10min.

$$^{13}N + p \rightarrow {}^{14}O + \gamma$$

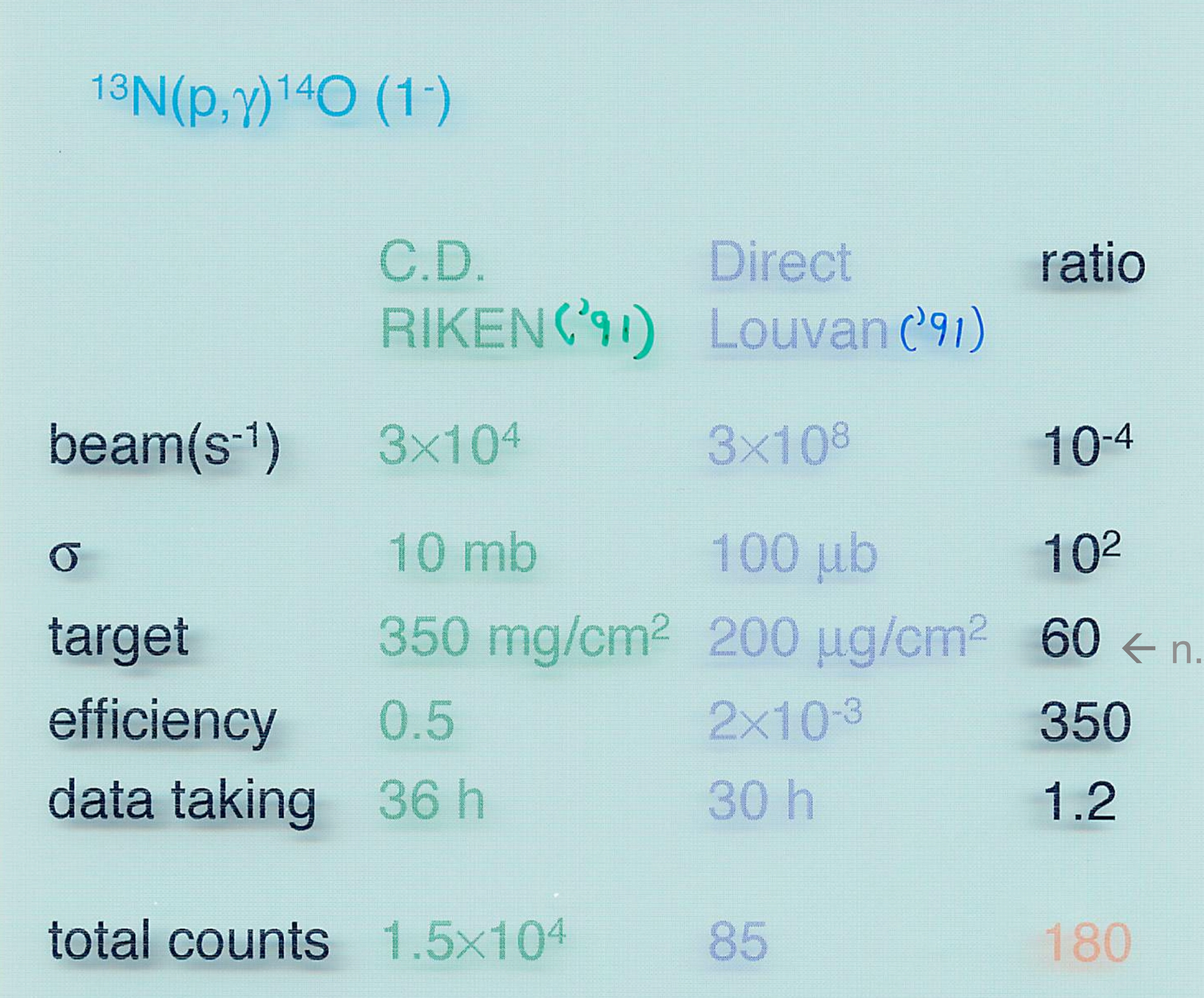
$\downarrow$ β^+

^{13}C



http://nrumiano.free.fr/Fetoiles/energie.html

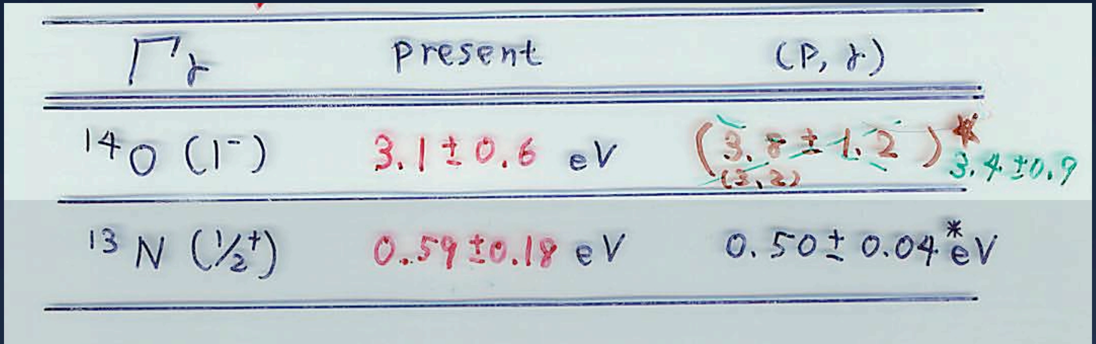
Coulomb dissociation is efficient.



$^{13}N(p,\gamma)^{14}O$ (1^-)

	C.D. RIKEN ('91)	Direct Louvan ('91)	ratio
beam(s^{-1})	3×10^4	3×10^8	10^{-4}
σ	10 mb	100 μb	10^2
target	350 mg/cm²	200 μg/cm²	60 ← n. of atoms
efficiency	0.5	2×10^{-3}	350
data taking	36 h	30 h	1.2
total counts	1.5×10^4	85	180

results -- measured radiative width / CNO hot-CNO boundaries

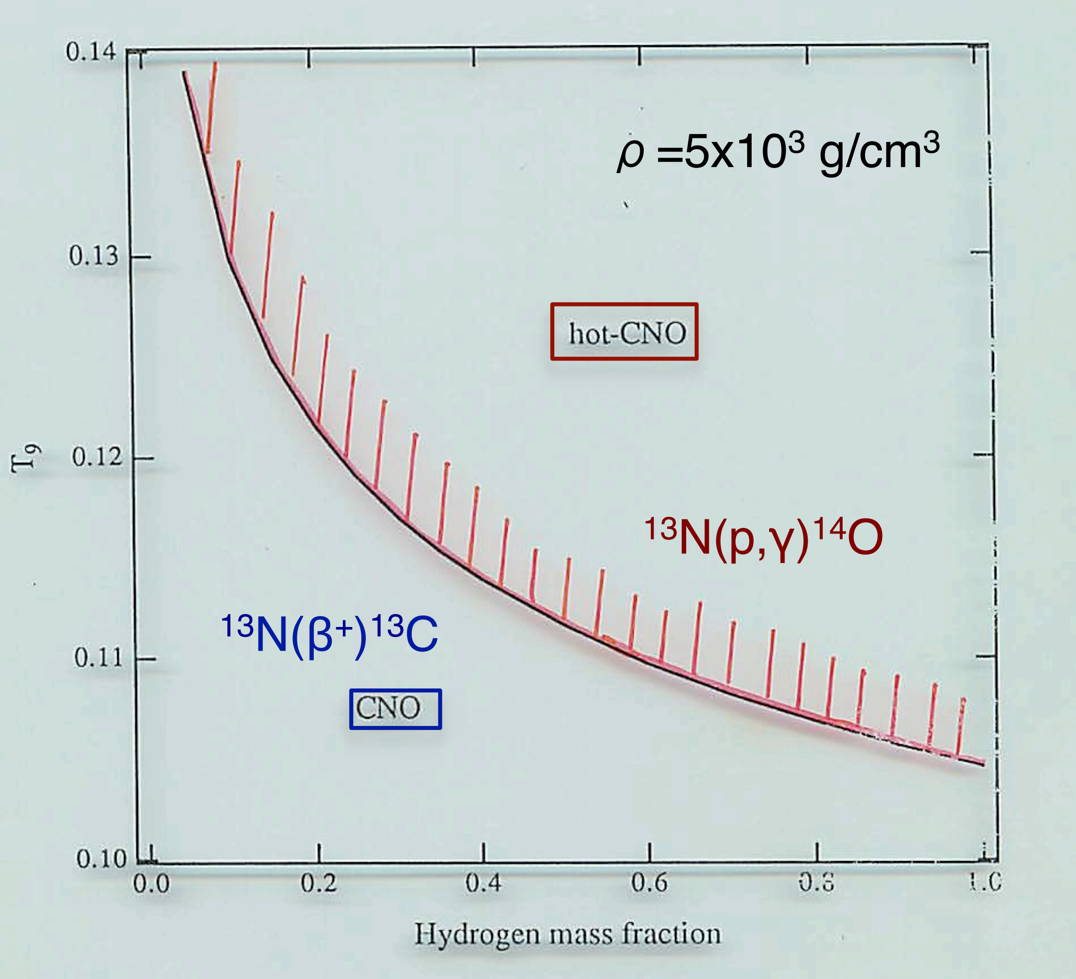


Γ_γ	present	(p, γ)
^{14}O (1^-)	3.1 ± 0.6 eV	~~(3.8 ± 1.2 (3.2))~~* 3.4 ± 0.9
^{13}N ($\frac{1}{2}^+$)	0.59 ± 0.18 eV	0.50 ± 0.04* eV

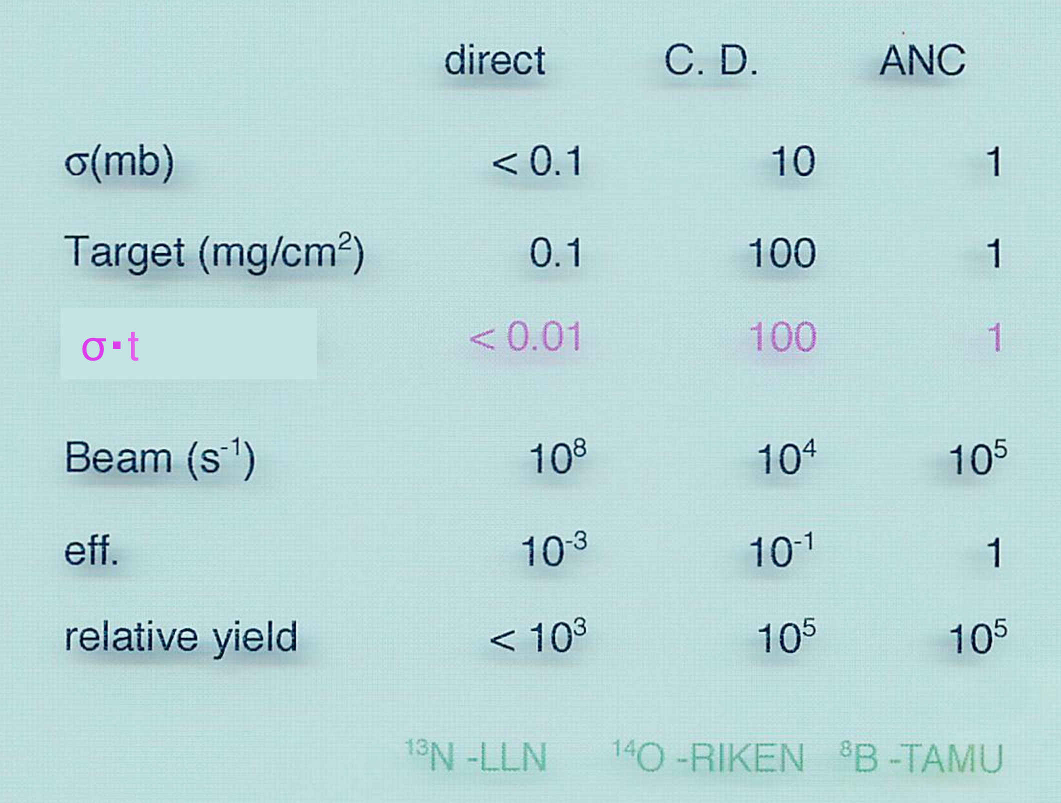
reaction rate <= $\omega\Gamma_\gamma$、E_0

$$\langle \sigma v \rangle \propto \omega \Gamma_\gamma (kT)^{-3/2} \exp\left[-\frac{E_0}{kT} \right]$$

$$P_{12} = \rho_1 \rho_2 \langle \sigma v \rangle$$



“typical” numbers for (p,γ) experiments



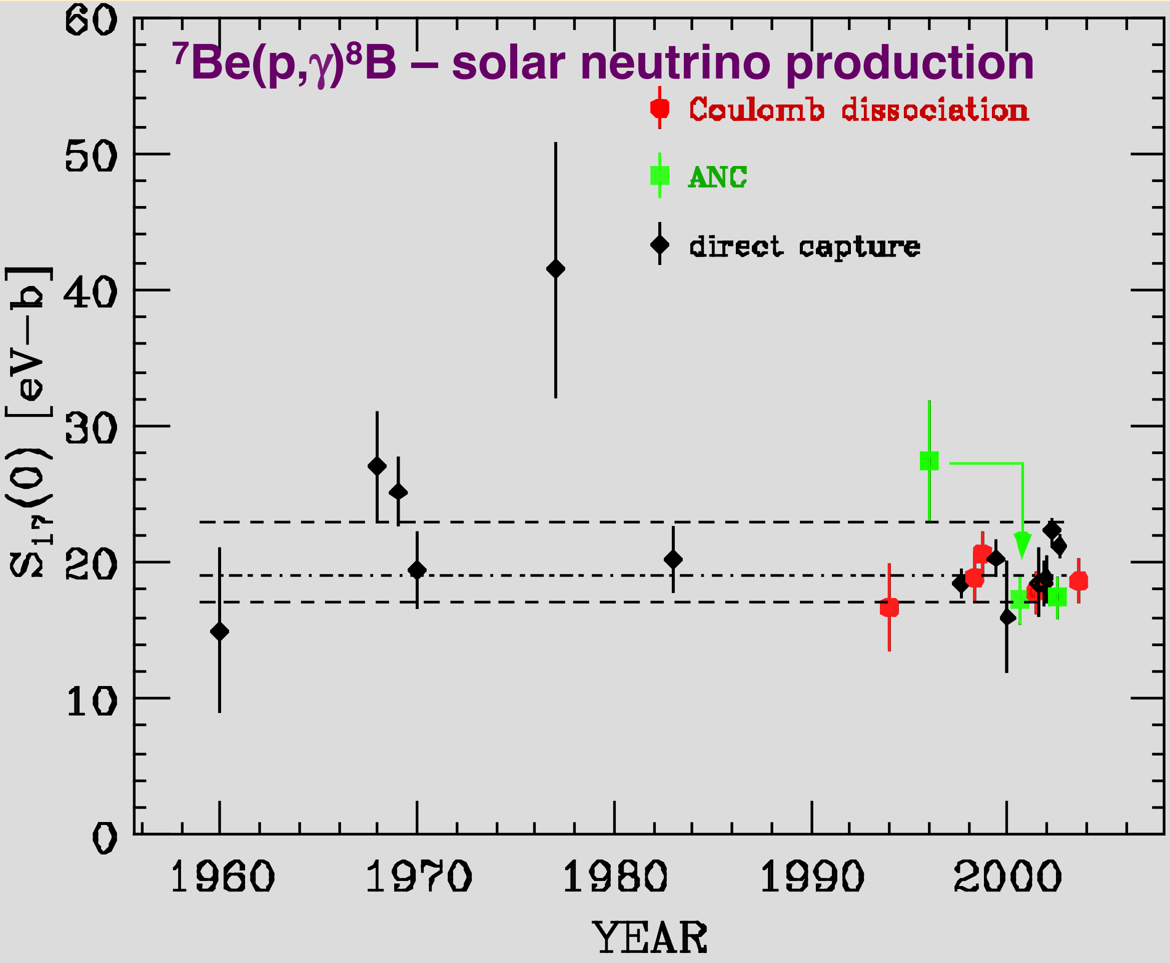
	direct	C. D.	ANC
σ(mb)	< 0.1	10	1
Target (mg/cm^2)	0.1	100	1
σ·t	< 0.01	100	1
Beam (s^{-1})	10^8	10^4	10^5
eff.	10^{-3}	10^{-1}	1
relative yield	< 10^3	10^5	10^5
	^{13}N -LLN	^{14}O -RIKEN	^{8}B -TAMU

ANC:
Asymptotic Normalization Coefficient
by transfer (breakup)

Indirect measurements appears to be better …

… but direct measurements have several advantages.

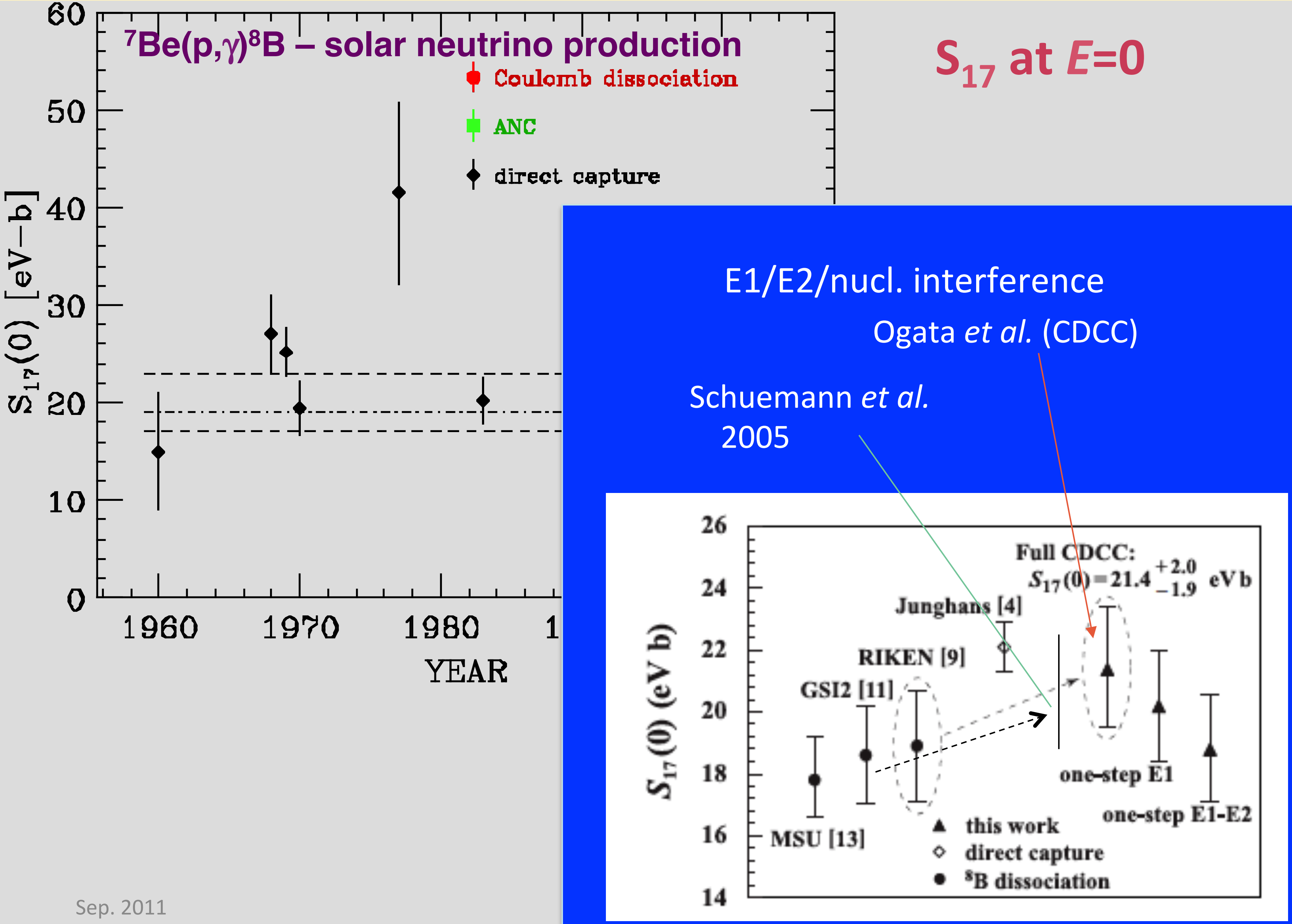
Recommended values change as experimental and theoretical development



S_{17} at E=0

Recommended values change as experimental and theoretical development

S_{17} at E=0



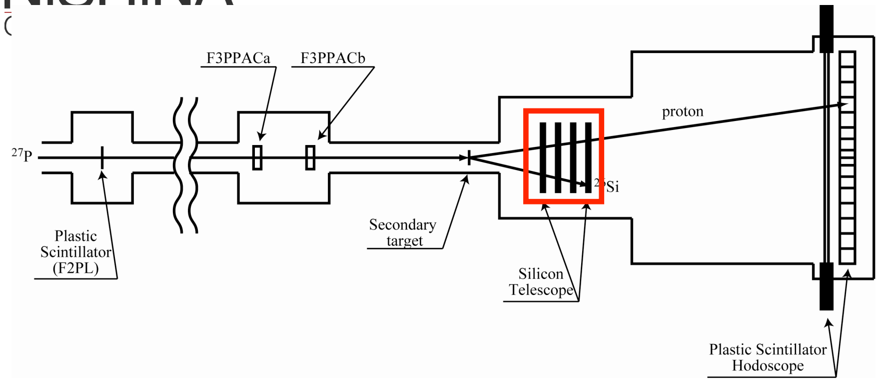
^{7}Be(p,γ)^{8}B – solar neutrino production

E1/E2/nucl. interference

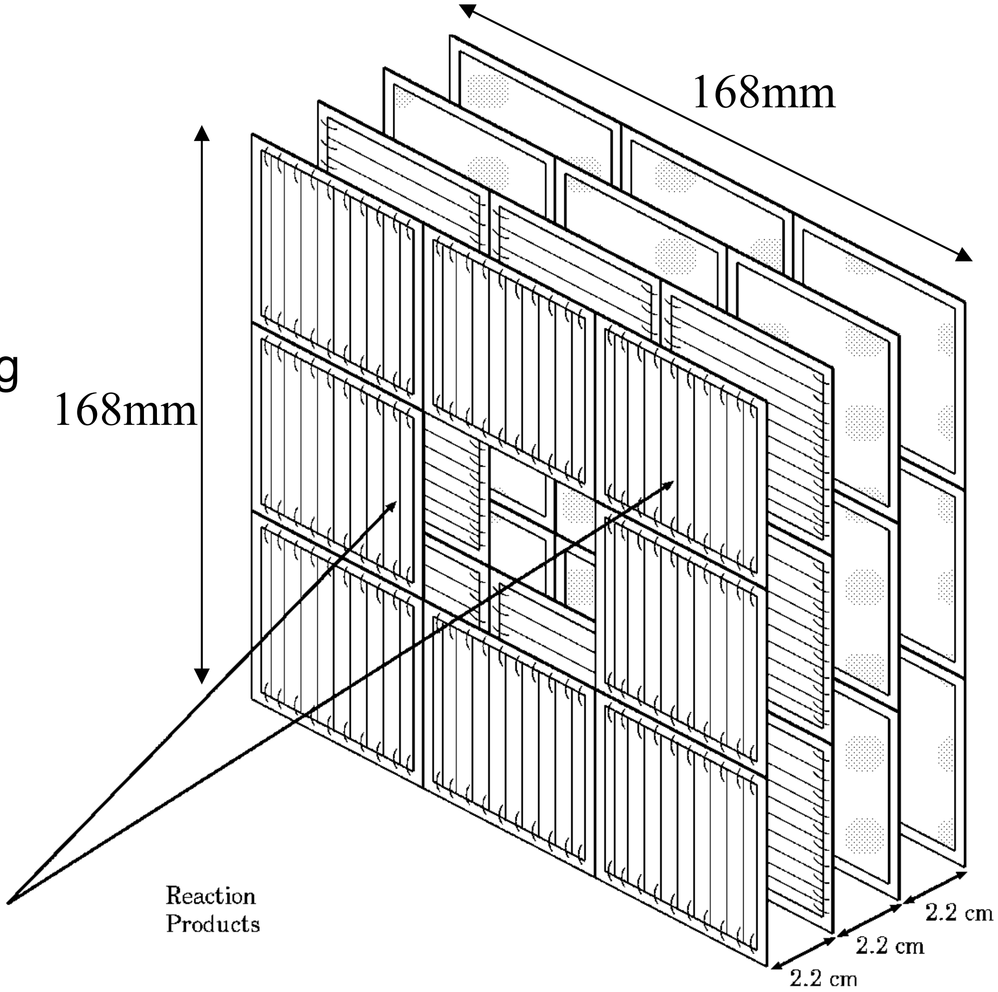
Ogata *et al.* (CDCC)

Schuemann *et al.*
2005

Silicon telescope



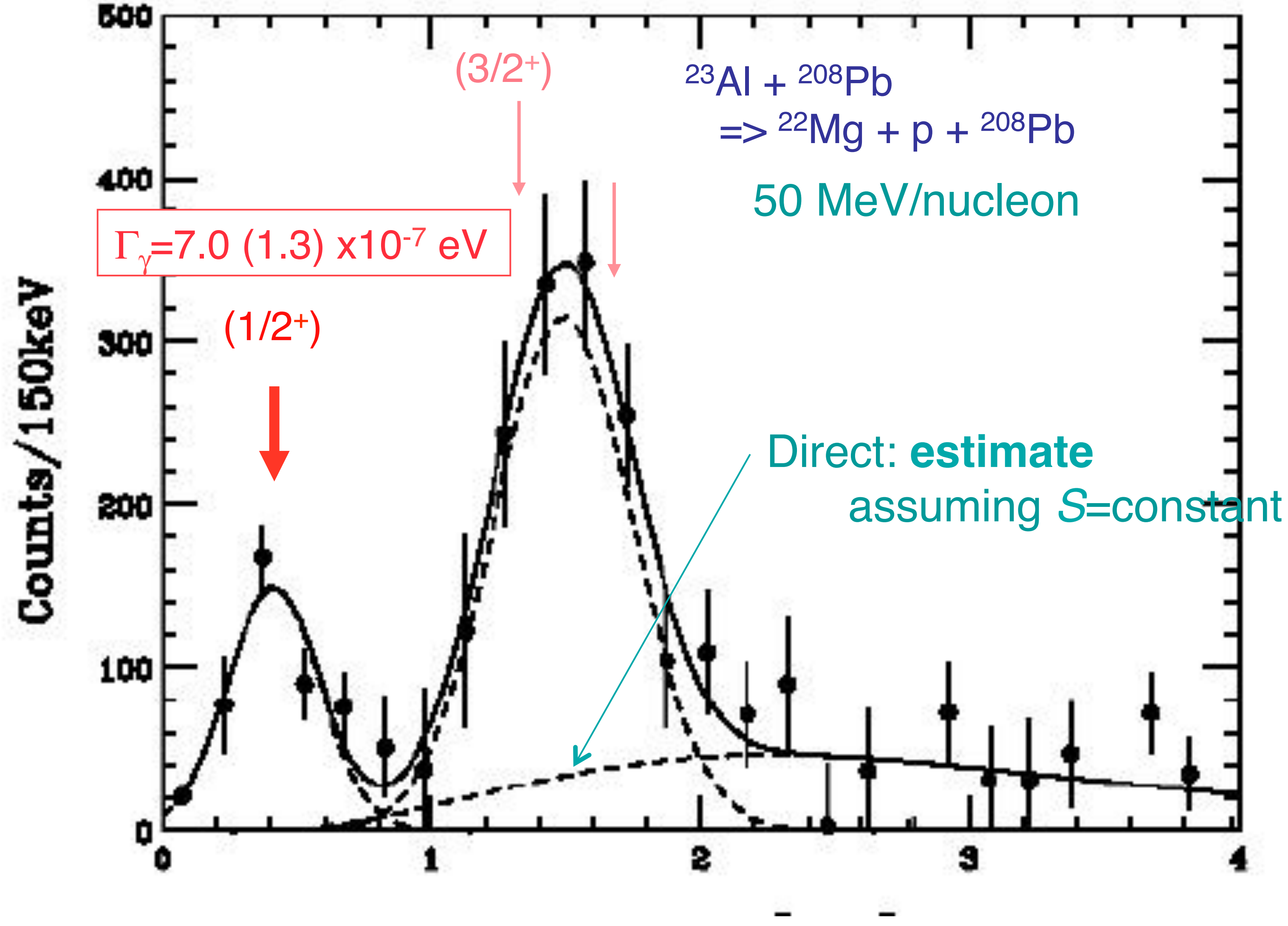
- Positions (angles) of proton and ^{22}Mg
- Kinetic enrgy of ^{22}Mg, isotope ID
  - 50 x 50 x 0.5 mm^3 Si x 8
  - Hole at the center
  - 4 layers to stop ^{22}Mg
  - 2 layers at upstream
    - 5mm strips for position
  - Other 2 layers: Single element



Proton energy by TOF

Coulomb dissociation - 10^4 pps ^{23}Al

←→10^{12} pps ^{22}Mg ! + ^{1}H



(3/2$^+$)

^{23}Al + ^{208}Pb
=> ^{22}Mg + p + ^{208}Pb

50 MeV/nucleon

Γ_γ=7.0 (1.3) x10^{-7} eV

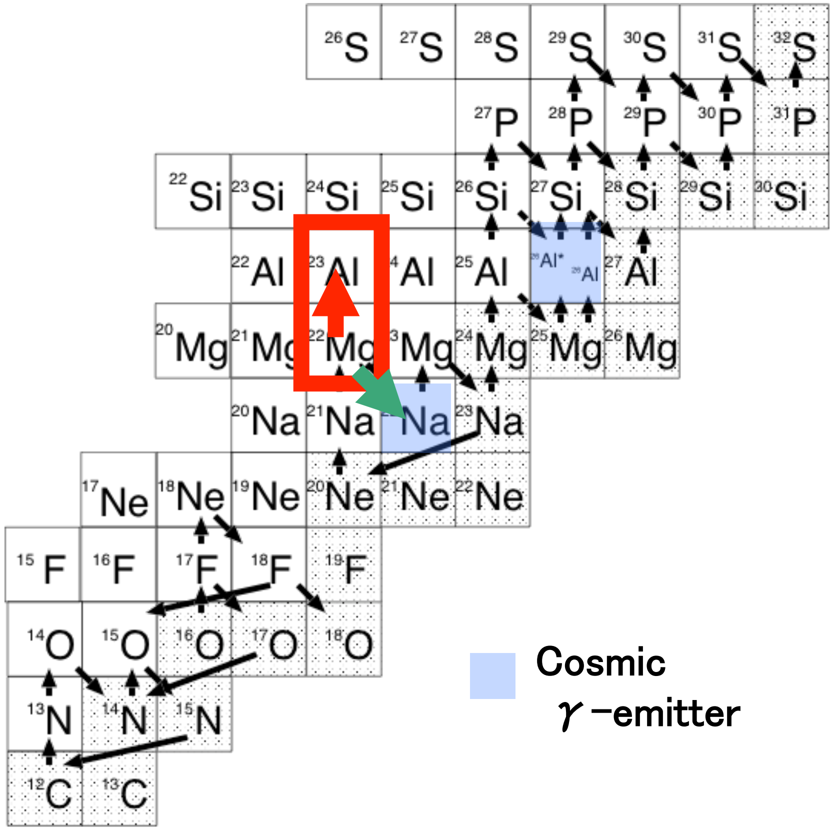
(1/2$^+$)

Direct: **estimate**
assuming *S*=constant

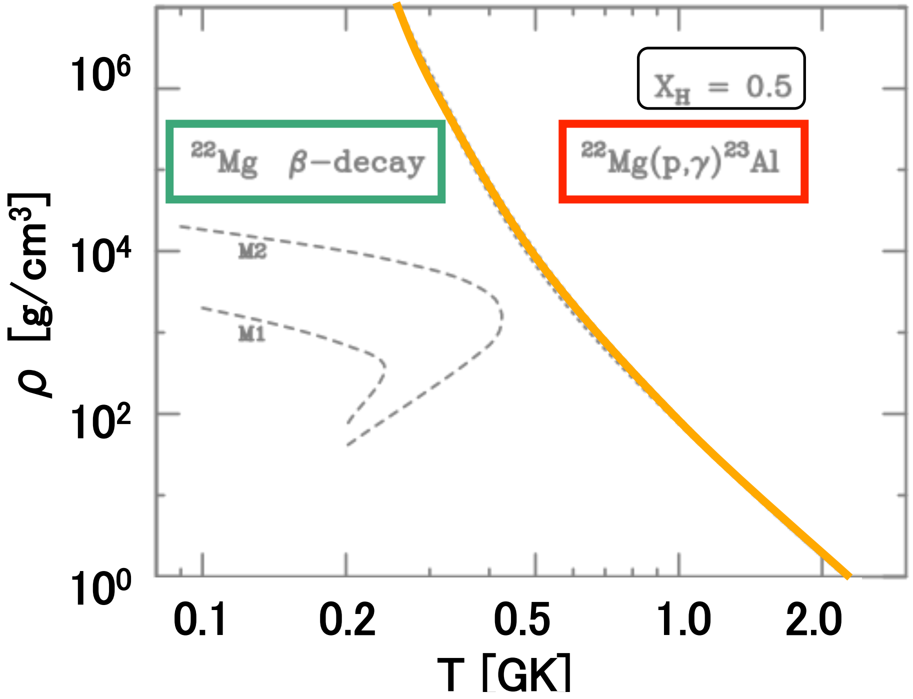
^{22}Mg-p relative energy [MeV]

^{22}Mg(p,γ)^{23}Al may not contribute in novae. <= our result

our resonance data w. direct component
→ reaction rate
→ competition with β decay



c.f. Lectures by Trache



Nova Model
M1 : J.Jose et al Astrophys. J. 520 347 (1999)
M2 : C. Iliadis et.al. Astrophys. J. Supp. 142 105 (2002)

In novae (←→ X-ray bursts)
β decay may be always favored.

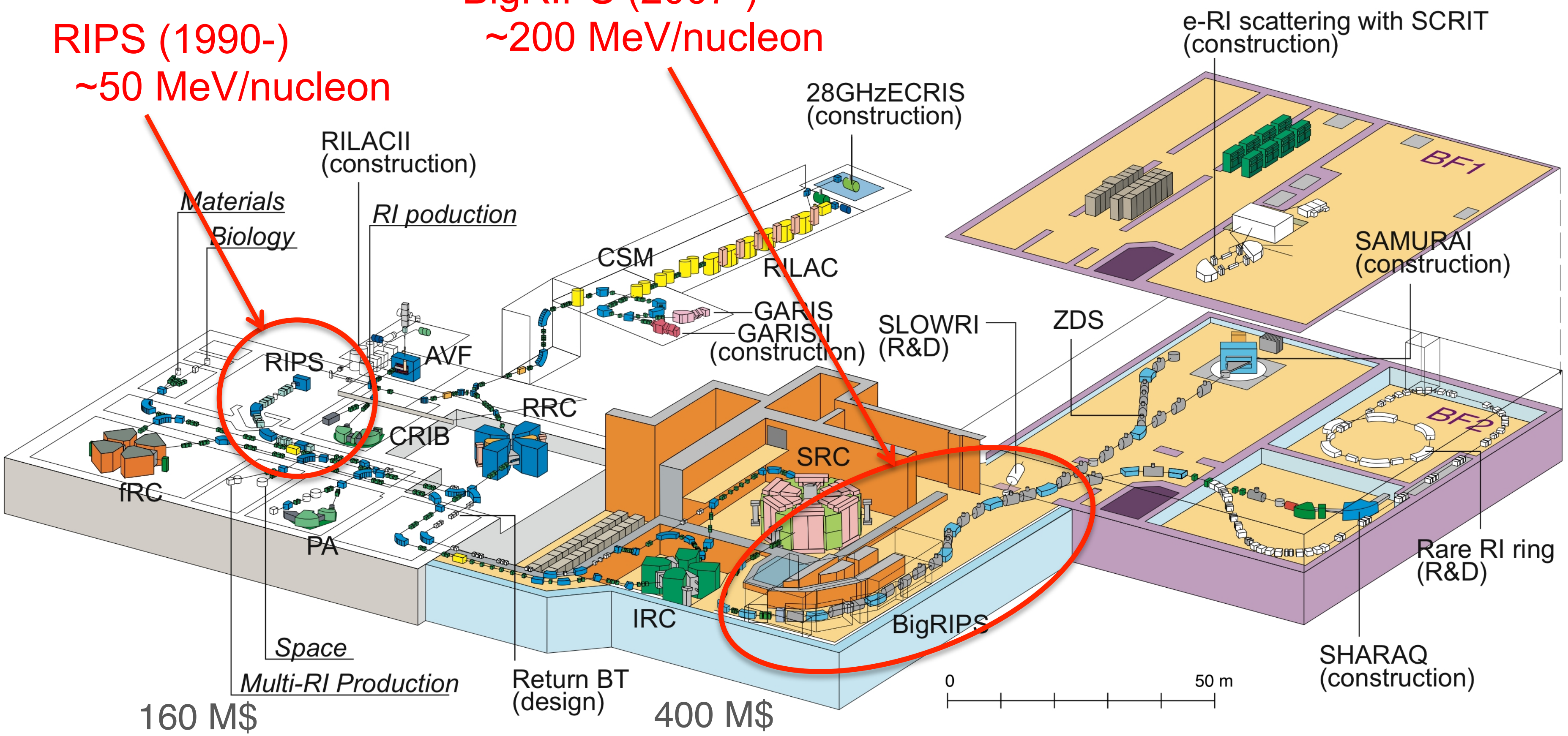
Similar work at RIKEN on ^{26}Si(p,γ)^{27}P: Togano et al., Phys. Rev. C 84. 035808 (2011)

RIBF new facility

RIBF – a new generation RIB facility in operation
with world highest capability of producing exotic nuclei in coming years!

RIPS (1990-)
~50 MeV/nucleon

BigRIPS (2007-)
~200 MeV/nucleon



160 M$
135 MeV/nucleon
for light nuclei (1986-)

400 M$
345 MeV/nucleon
up to U (2006-)

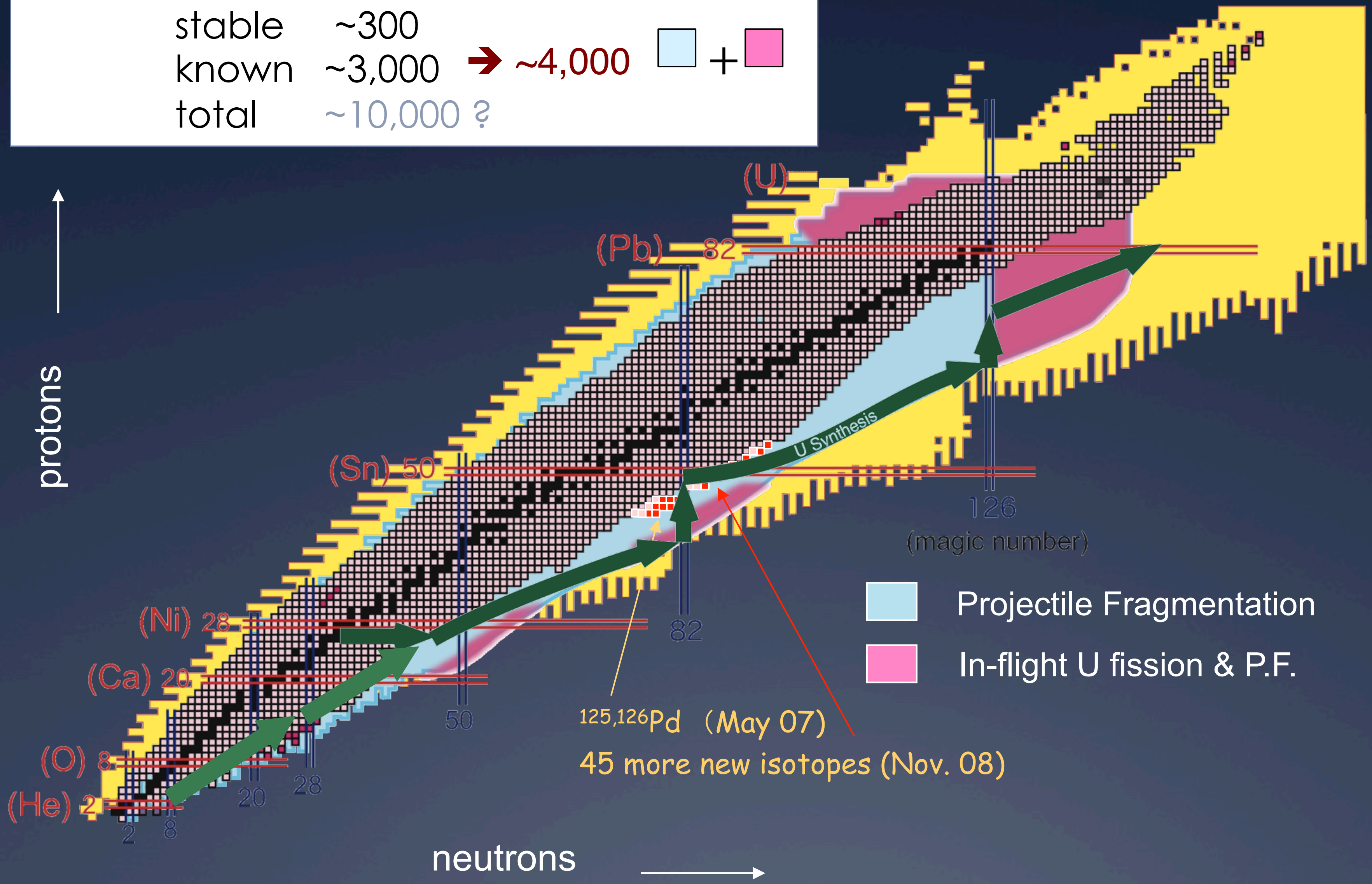
experimental
equipment

Atomic nuclei (isotopes)

stable	~300	
known	~3,000	➔ ~4,000 ☐ + ☐
total	~10,000 ?	

> 1 particle/day (Goal Intensity)

(EPAX predicition)



^{125,126}Pd (May 07)

45 more new isotopes (Nov. 08)

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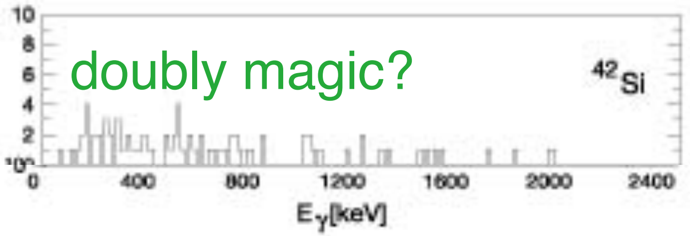
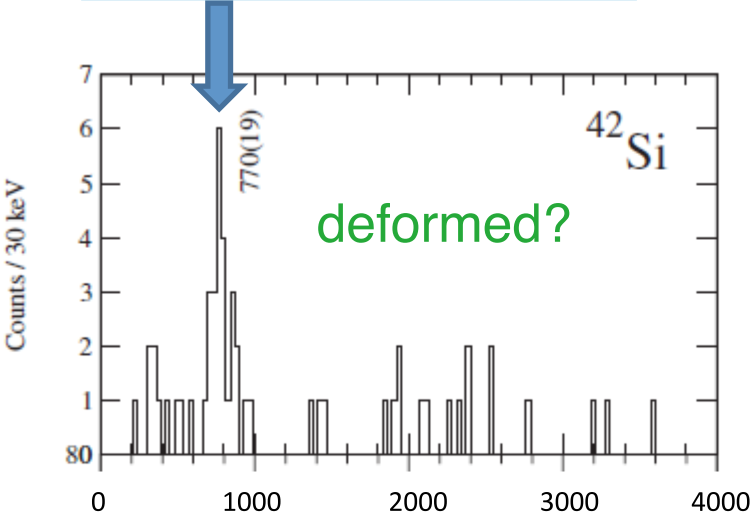
“doubly magic” ^{42}Si (Z=14, N=28) - confirmation of the low-lying 2$^+$ / higher states



NSCL → Fridman et al. Nature, PRC74(2006)
(No low-energy peak, small 2p removal σ)

Energy	~100*A* MeV
Intensity Integral	1x10^8 Particles

2006 GANIL data (? days)



GANIL → Bastin et al. PRL 99(2007)022503

Energy	~40*A* MeV
Intensity	~125 cps

Takeuchi *et al.*
2010 RIKEN data (~90 hours)

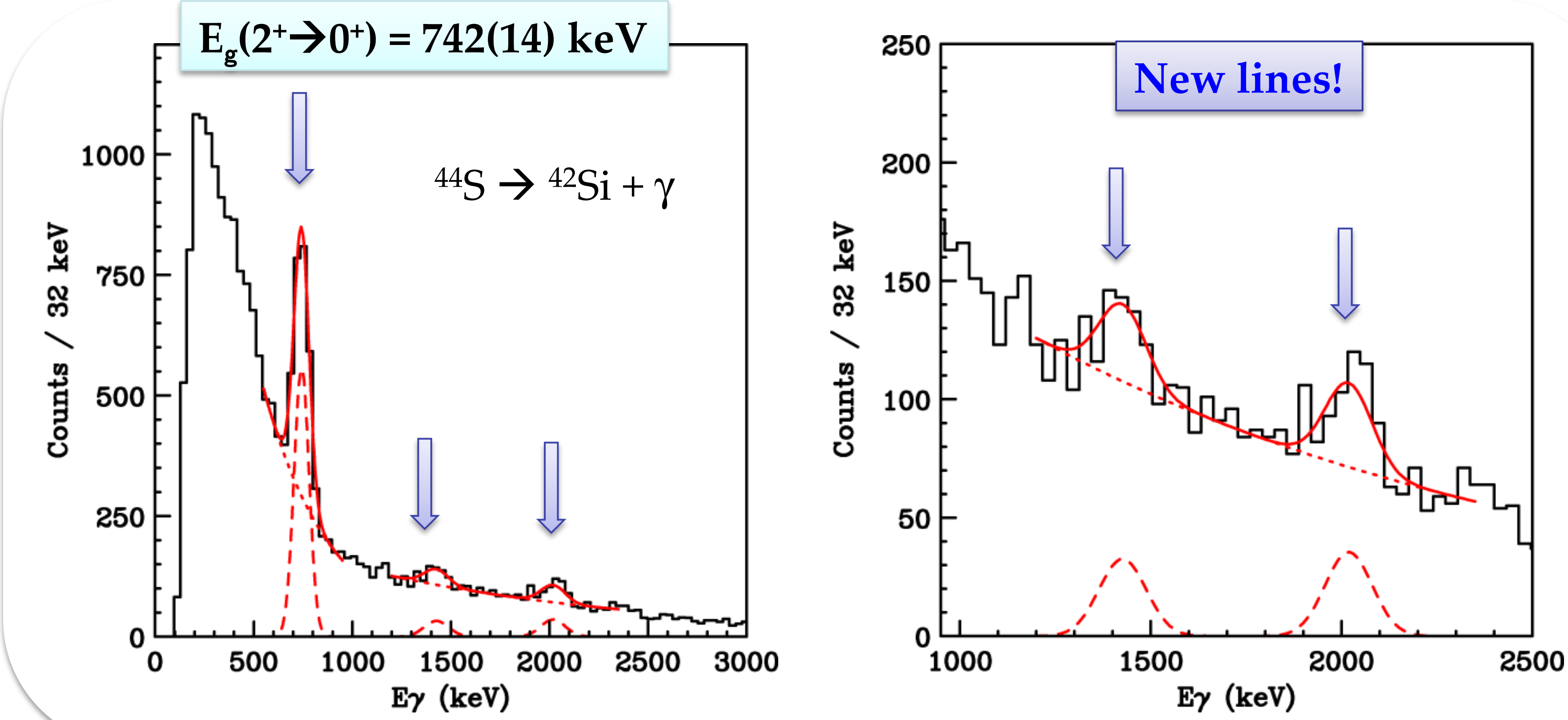
^{44}S → ^{42}S+γ
200 *A*MeV, 40,000 cps

High RI beam intensity
x300 of GANIL
x100 of MSU – integral
High DALI2 efficiency

high statistcs
→γ-γ coincidence
→states above 2$^+$

Results - γ single spectrum -

*Widths are fixed to simulated values.



$E_g(2^+ \rightarrow 0^+)$ = 742(14) keV

New lines!

GANIL exp. : 770(19) keV
B.Bastin et al., Phys. Rev. Lett. 99, 022503 (2007).

We confirmed the γline observed at GANIL.

“Seven Samurai”, movie by Akira Kurosawa (1954)

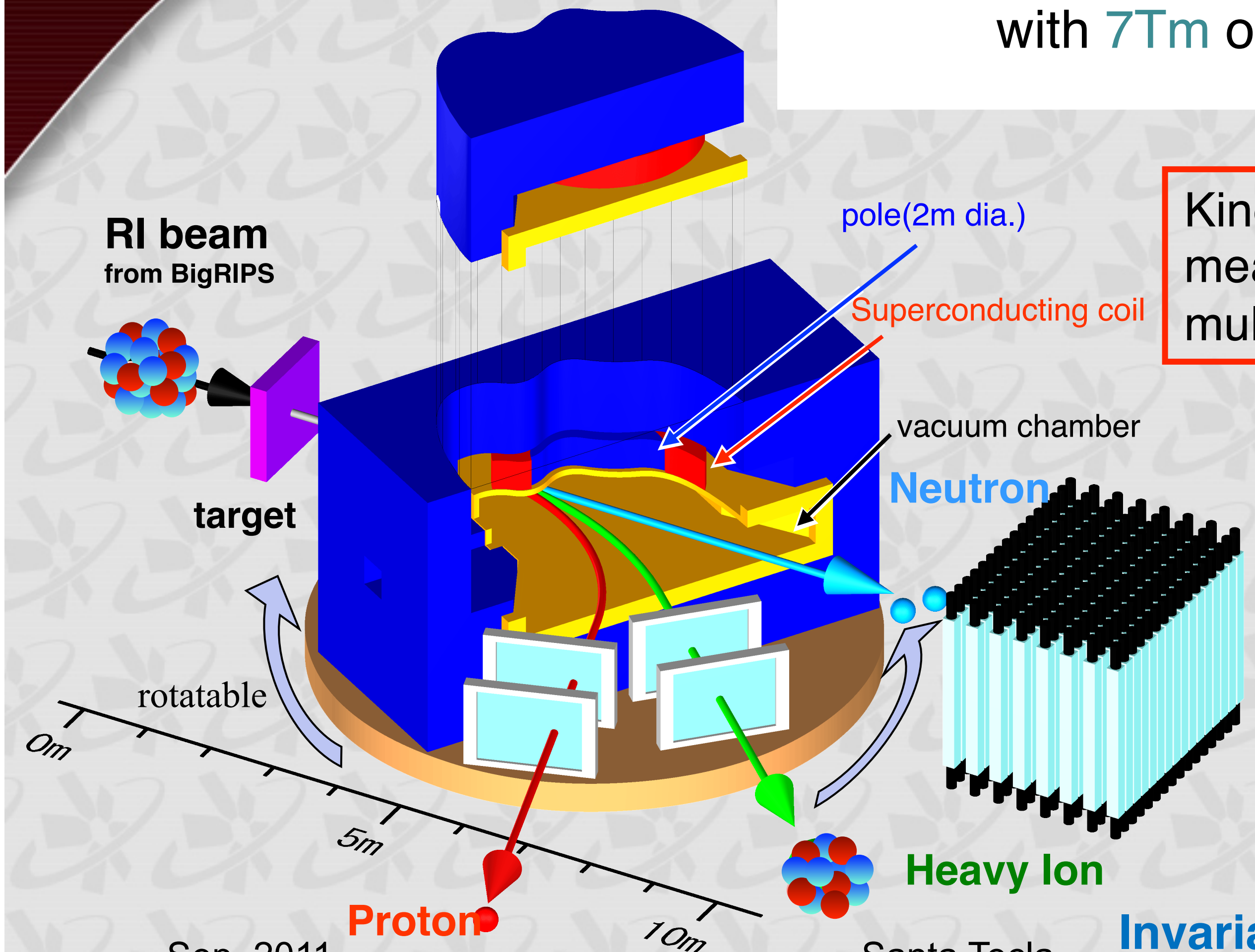
Superconducting coils have been successfully excited.

Apr. 2011

SAMURAI

-- new spectrometer in RIBF --

Superconducting **A**nalyzer for **MU**lti-particle
from **RA**dio **I**sotope Beam
with 7Tm of bending power



Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

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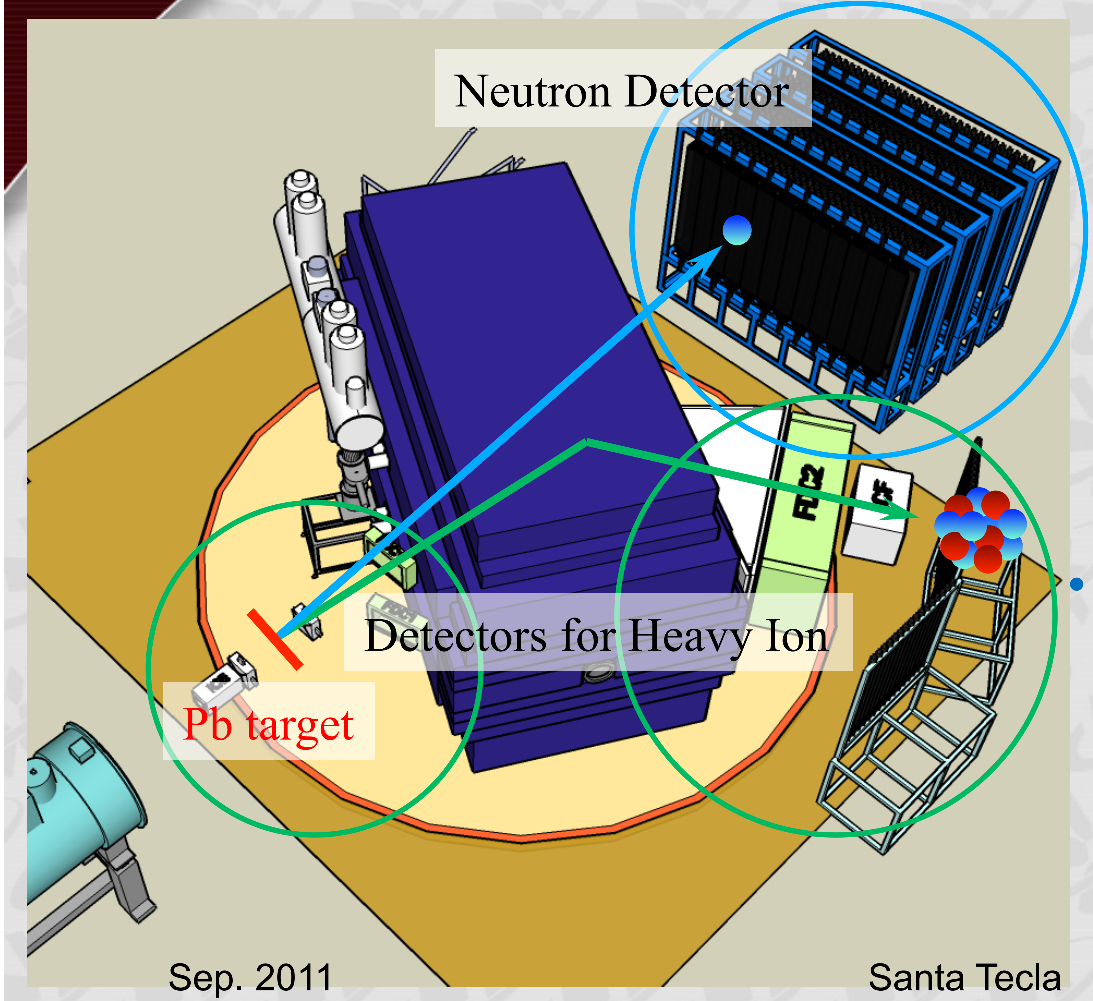
Invariant Mass Measurement
Missing Mass Measurement

Detector System - (γ, *n*) measurement (CD) mode

(γ, *n*) reaction: neutron-rich side



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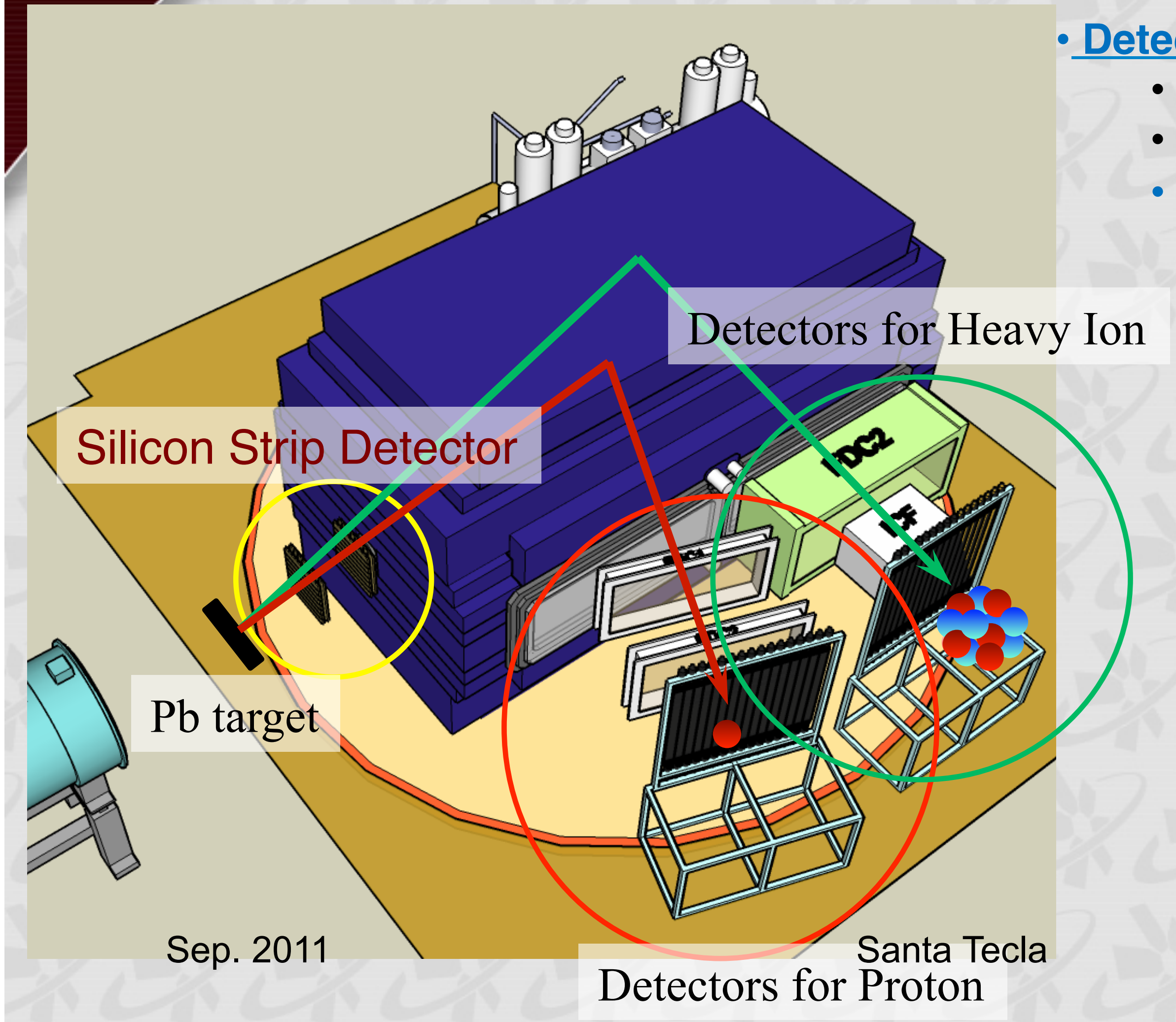
- **Detectors for Heavy Ion**
  - Position measurement
    - Drift Chambers
      Beam
      Fragments before/after
  - Charge measurement
    - Ion Chambers
      Beam / Fragments
  - Velocity measurement
    - Plastic hodoscope
    - Cherenkov counter
  - Total E measurement
    - Pure CsI detector
- **Neutron Detector**
  - Plastic scintillator
    - 240 modules
      (120mm x120mm x1.8m / module
    - Effective Area: 3.6 m (H) × 1.8 m (V)
      ~ 100 % coverage @ $E_{\mathrm{rel}} <$ 3 MeV
      ~ 40 % coverage @ $E_{\mathrm{rel}} \sim$ 10 MeV
    - Efficiency ~ 66 % (Harf: ~40 %)

Half volume is ready

Detector System - (γ, *p*) measurement mode

(γ, *p*) reaction: proton-rich side



- **Detectors for Heavy Ion**
  - same as (γ,n)
- **Detectors for Proton**
  - Proton Drift Chamber
  - Plastic Hodoscope
  - **Silicon Strip Detector**

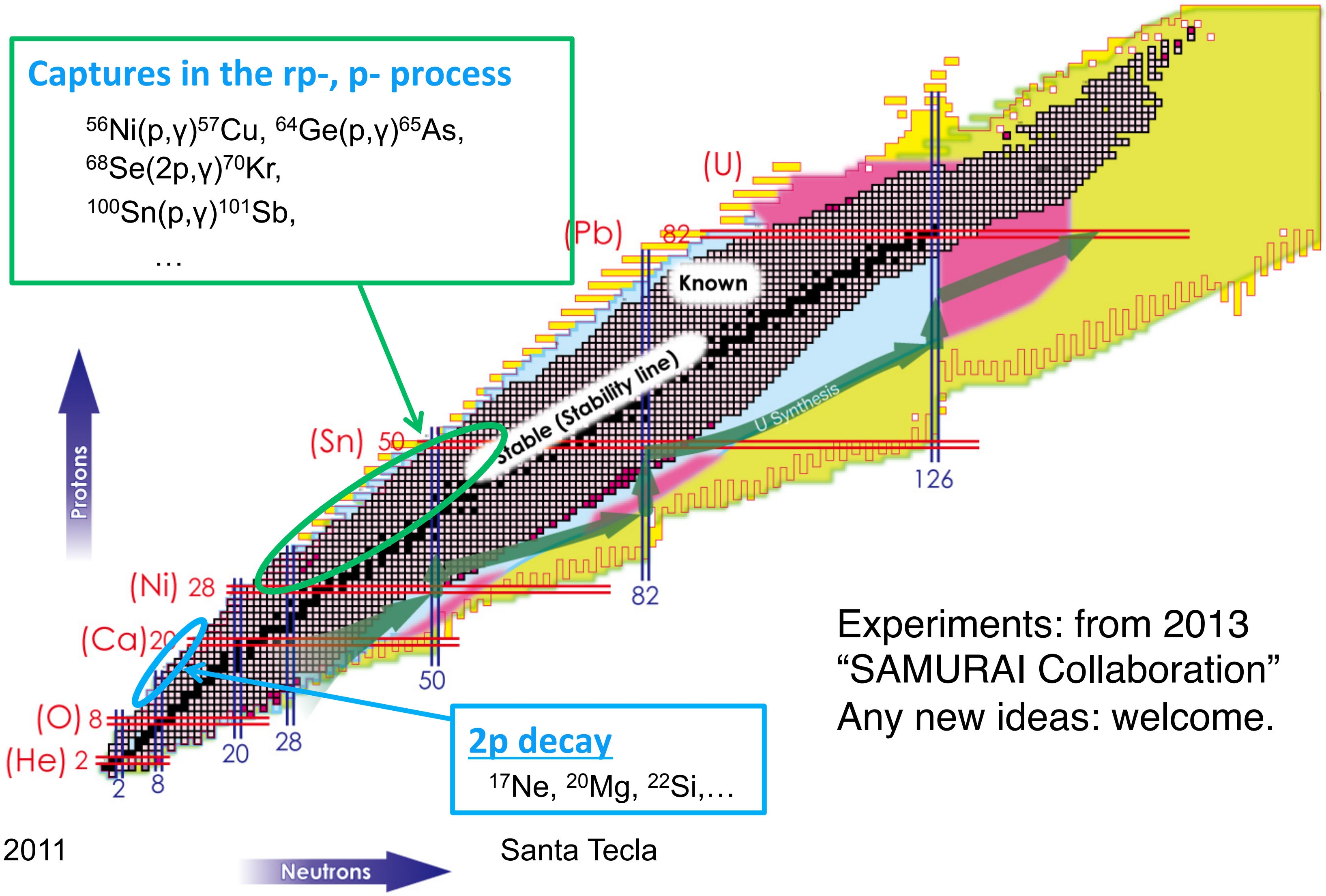
    \- Broad dynamic range (~10,000)
    Both proton & heavy ion (Z < 50) hit the detector

    \- High density signal processing
    Signals of about 2500ch in total

Under development
Based on ASIC technology
in collaboration with
Texas A&M Univ. and
Washington Univ. in St. Louis
HINP16C --- 16ch processing in 1 chip
two output for energy and timing

Capability for 2p capture cases

Possible experiments in the first stage



Captures in the rp-, p- process

^{56}Ni(p,γ)^{57}Cu, ^{64}Ge(p,γ)^{65}As,
^{68}Se(2p,γ)^{70}Kr,
^{100}Sn(p,γ)^{101}Sb,
…

2p decay

^{17}Ne, ^{20}Mg, ^{22}Si,…

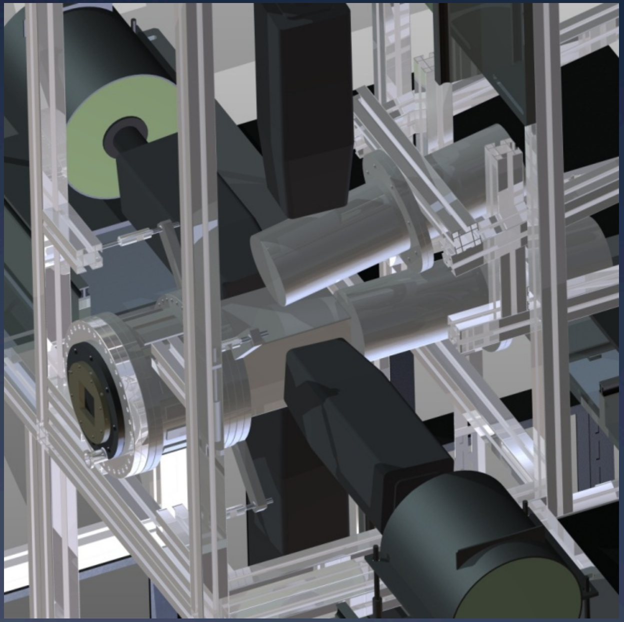
Experiments: from 2013
“SAMURAI Collaboration”
Any new ideas: welcome.

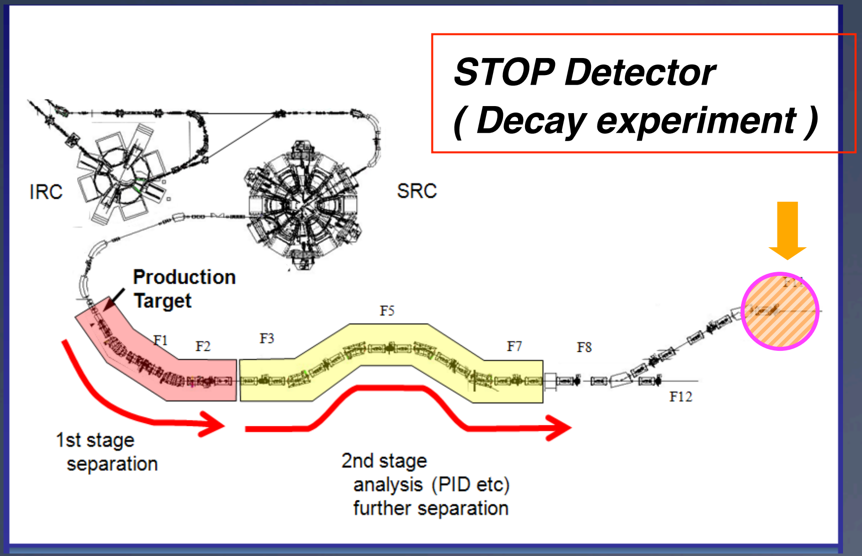
Toward the r-process path at the RIBF new facility: 1st β decay measurements

Nishimura, Sumikama, *et al.*

2009 Dec.
U beam to access A~110 region
Intensity 0.8 pnA max.
0.1-0.2 pnA on average
(1/10000 – 1/1000 of the RIBF goal)

Half life measurements for r-process nuclei
Beta-gamma spectroscopy
Delayed gamma spectroscopy for isomers

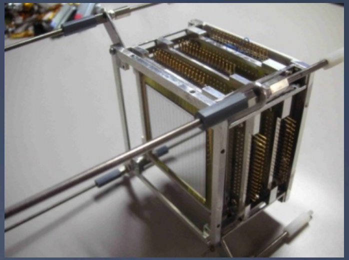




STOP Detector
(Decay experiment)

1st stage separation

2nd stage
analysis (PID etc)
further separation

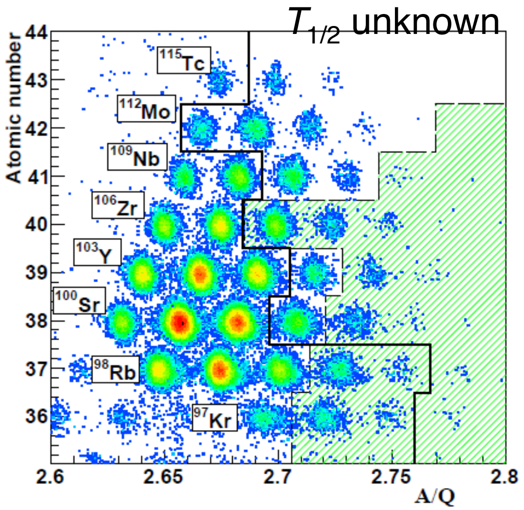


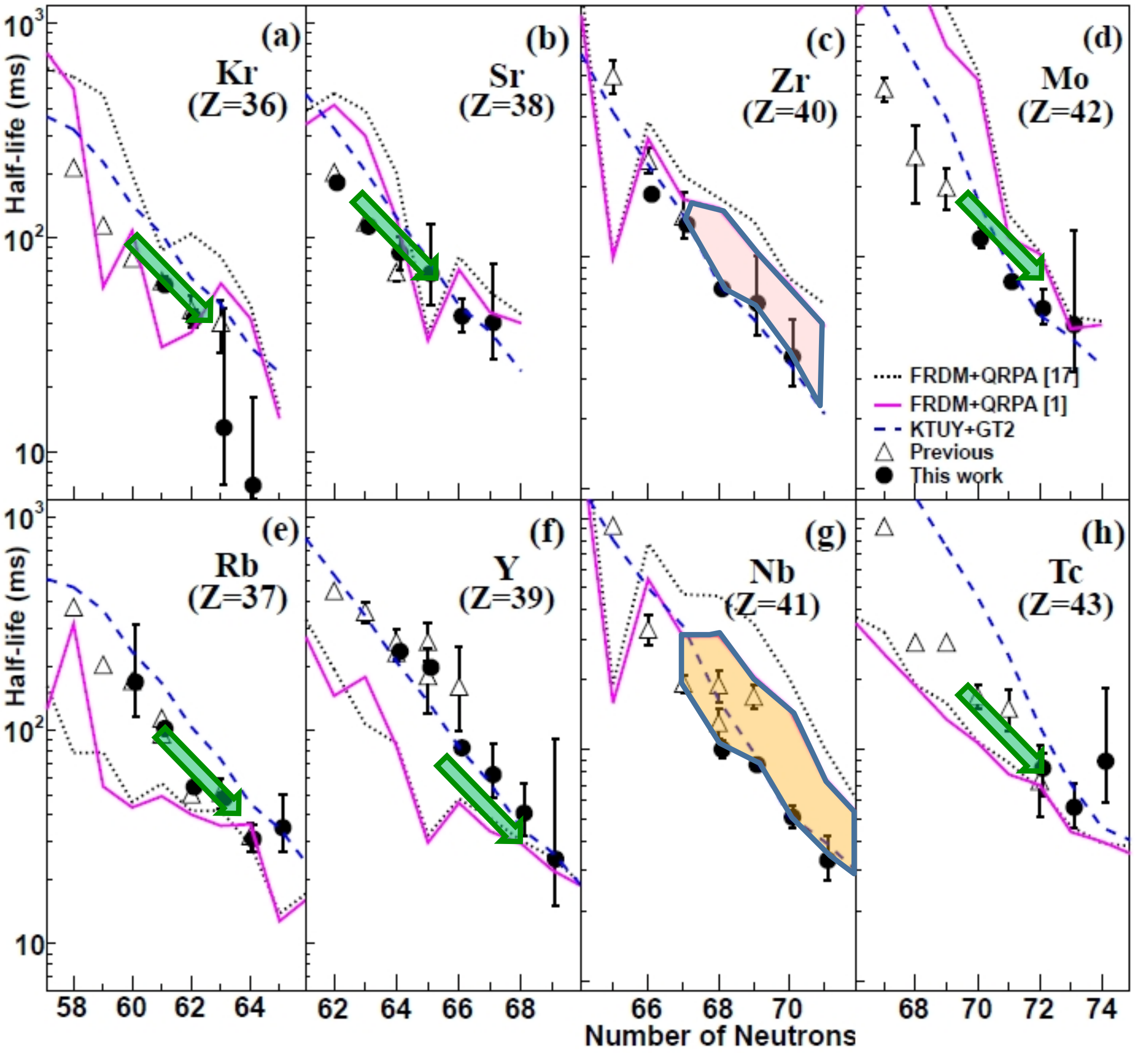
Clovers (RIKEN)
$LaBr_3$ (Milano)
9 layers of DSSD (RIKEN, TUS)

Toward the r-process path at the RIBF new facility - β decay half-life

Systematic studies of $T_{1/2}$ ←→ Mass, Q_β, S_n

Nishimura *et al.* PRL106, 052502 (2011)





- 8 hours data acquisition
- *T*1/2 data of 38 isotopes including **first data for 18 isotopes**

$T_{1/2}$ are shorter for Zr/Nb compared with FRDM theories!

Summary

Cross section determination is important in light nuclei (low-level density).

Coulomb dissociation, an indirect tool for astrophysical capture processes, is powerful for the cases involving unstable nuclei.

SAMURAI at RIKEN RIBF will provide new opportunities of astrophysical (p,γ) and (n,γ) studies (Coulomb dissociation).

Studies of near and in the r-process path are to be made at RIKEN RIBF, which has currently the world highest capability of RI beam production.

Visit http://www.rarf.riken.jp/Eng/facilities/RIBF.html.
Join “collaborations”.

Thank you!

Grazzii

ありがとうございました